# When should green technology support policies supplement the carbon price? The case of the electricity sector

Oskar Lecuyer

CENTRE INTERNATIONAL DE RECHERCHE EN ENVIRONNEMENT ET DÉVELOPPEMENT

ÉCOLE DES HAUTES ÉTUDES EN SCIENCES SOCIALES

EDF RECHERCHE & DÉVELOPPEMENT

# QUELLE PLACE POUR LES AIDES AUX TECHNOLOGIES DE RÉDUCTION D'ÉMISSIONS EN PRÉSENCE D'UN PRIX DU CARBONE ? LE CAS DU SECTEUR ÉLECTRIQUE

# WHEN SHOULD GREEN TECHNOLOGY SUPPORT POLICIES SUPPLEMENT THE CARBON PRICE? THE CASE OF THE ELECTRICITY SECTOR

Thèse pour l'obtention du grade de docteur de l'EHESS en sciences économiques, présentée le 29 novembre 2013 par

OSKAR LECUYER

Sous la direction de

PHILIPPE QUIRION

devant le jury constitué de

| | | |
|---|---|---|
| JEAN-CHARLES HOURCADE | Directeur de recherche, CNRS et Directeur d'études, EHESS | Président |
| CLAUDE CRAMPES | Professeur émérite d'Economie à la Toulouse School of Economics (UT1) | Rapporteur |
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| ANNA CRETI | Professeur des Universités, Université Paris Dauphine | |
| CAROLYN FISCHER | Senior Fellow and Associate Director, Resources for the Future | |
| BENOÎT PELUCHON | Ingénieur-Chercheur, EDF R&D | Encadrant industriel |
| PHILIPPE QUIRION | Directeur de recherche, CNRS | Directeur de thèse |

OSKAR LECUYER

*Quelle place pour les aides aux technologies de réduction d'émissions en présence d'un prix du carbone ?
Le cas du secteur électrique,*

*When should green technology support policies supplement the carbon price?
The case of the electricity sector,*

LABORATOIRE D'ACCUEIL :
Centre International de Recherche en Environnement et Développement, Campus du Jardin Tropical, 45 bis, avenue de la Belle Gabrielle, 94736 Nogent-sur-Marne Cedex, France

THÈSE CIFRE RÉALISÉE AVEC LE SOUTIEN DE :
EDF R&D, Département EFESE, 1, Avenue du Général de Gaulle, 92140 Clamart Cedex, France

# RÉSUMÉ

Cette thèse étudie les conditions d'efficacité d'un portefeuille de politiques pour réduire les émissions de gaz à effet de serre du secteur électrique. Il est montré qu'en présence d'incertitude, le prix du carbone issu d'un marché de permis d'émissions peut ne pas entraîner suffisamment de réductions d'émission, justifiant l'ajout d'une politique au marché de permis, par exemple une subvention renouvelable. Dans le cadre d'une transition vers une production électrique décarbonée, l'accumulation du capital électrique génère des effets dynamiques complexes. Il est montré que l'utilisation naïve du signal-prix du carbone ou de critères statiques pour évaluer les investissements peut alors conduire à un sous-investissement en capital vert. L'effet d'une modification à la marge du portefeuille de politiques actuel est également étudié. Il est montré en particulier que si on suppose une seule technologie de production fossile à taux d'émission constant, contrainte par un plafond d'émissions — donc toutes les réductions d'émissions proviennent des renouvelables — augmenter à la marge le tarif d'achat renouvelable réduit le prix de l'électricité perçu par le consommateur, et ce paradoxalement même si la taxe à la consommation nécessaire pour financer le tarif augmente. Cette thèse réalise enfin une évaluation qualitative du portefeuille actuel de politiques climat-énergie en France. Cet examen montre que les multiples défaillances du prix du carbone justifient l'utilisation d'une combinaison de politiques, même si le portefeuille cible varie en fonction des hypothèses sur les trajectoires du prix du carbone.

# ABSTRACT

This thesis contributes to the literature on optimal policy choice. It studies the use of policy combinations to mitigate greenhouse gases emissions from electricity production. One finding applies to cases where uncertainty is such that the risk of a nil carbon price cannot be excluded. A cap on emissions alone may then not trigger enough abatements, justifying the addition of e.g. a renewable subsidy. When considering a transition toward a carbon-free electricity sector, capital accumulation causes complex dynamic effects to happen. We find that decisions taken by comparing the levelized costs of abatement technologies, even including carbon costs, would favor intermediate technologies (e.g. gas plants) to the detriment of more-expensive but lower-carbon technologies (renewable power), leading to a suboptimal investment schedule. This thesis also studies the effects of marginal policy changes in a mix comprising the main French instruments. We find that surprisingly, adding a tariff for renewables financed by a tax on electricity consumption to a cap on emissions and a subsidy for energy efficiency will reduce the consumer electricity price when the non-renewable production is fixed and does not depend on the carbon price. The assessment of the French climate policies in the electricity sector shows that overlapping policies for mitigation may be justified by multiple carbon price failures, even if the ideal long-term policy mix depends on the carbon price trajectory.

# MOTS CLÉS

Atténuation du changement climatique Capital vert Coûts actualisés de l'électricité Combinaisons de politiques Dépendance au sentier Dépréciation Effets de filière Efficacité énergétique Énergies renouvelables Incertitude Interactions Politiques énergétiques Politiques climatiques Politiques technologiques Prix de l'électricité Taux d'utilisation Transition énergétique

# KEYWORDS

Climate change mitigation Climate policy Congestion costs Corner solutions Electricity price Electricity sector Energy efficiency Energy policy European Union EU-ETS Levelized costs Mitigation policy Nil $CO_2$ price Optimal timing Path dependence Policy interaction Policy overlapping Renewable energy Technology policy Uncertainty

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*Can uncertainty justify overlapping policy instruments to mitigate emissions ?*, 2012. in : International Association for Energy Economics IAEE : European conference, Venice, Italy.

*Can uncertainty justify overlapping policy instruments to mitigate emissions ?*, 2013. in : IDEI conference : The Economics of Energy Markets, Toulouse, France.

*Can uncertainty justify overlapping policy instruments to mitigate emissions ?*, 2013. in : 20th Annual Conference of the European Association of Environmental and Resource Economists, Toulouse, France.

# REMERCIEMENTS

J'exprime en premier lieu ma gratitude aux rapporteurs et aux membres du jury pour avoir accepté de lire et évaluer ce travail : Claude Crampes et Carolyn Fischer qui ont consenti à faire le trajet depuis Toulouse et même Washington, Anna Créti et Jean-Pierre Ponssard qui ont apporté de nombreux commentaires constructifs pour valoriser ce travail. Cette thèse n'aurait pas vu le jour sans Philippe Quirion, qui a su mettre la mettre dans les bons rails et a su la diriger sans contraindre, ni sans l'action déterminante et le soutien sans faille de Jean-Charles Hourcade, qui de surcroît a accepté de présider le jury. Je leur exprime ici toute ma reconnaissance.

Je remercie également toute l'équipe d'EDF R&D, pour son acceuil et l'ambiance de travail du plateau de Clamart : Chantal Degand pour sa supervision bienveillante, Benoît Peluchon et Michèle Dhaussy puis Viviane Leboucher qui ont suivi et encadré la thèse avec un intérêt grandissant. Je salue le reste de l'équipe de recherche, avec qui j'ai eu des échanges constants et formateurs : Denis Picon, Maud Imberty, Lionel Cauret et d'autres qui auraient mérité de figurer ici, ainsi que les thésards CIFRE grâce à qui j'ai franchi beaucoup d'obstacles : Ibrahim Abada, Claire-Marie Bono, Romain Riollet et Alvaro Andaluz. Je suis de plus tout particulièrement reconnaissant à Mourad Ayouz, Paul Baudry et Marc Trotignon pour leur appui inespéré et précieux quand le besoin s'en faisait sentir.

J'adresse également un chaleureux remerciement à toute l'équipe du CIRED, mes co-autheurs, collègues et amis : Adrien Vogt-Schilb, Ruben Bibas et Frédéric Branger, et les thésards du CIRED que j'ai eu le plaisir de fréquenter (dans l'ordre alphabétique) — la plupart ont soutenu entre-temps, pour leur relecture, leur inspiration, leur conversation et leur soutien : Benoit Allibe, Cédric Allio (qui n'a pas d'égal sur le plan technique), Paolo Avner, Meriem Hamdi-Cherif (qui n'a eu de cesse d'apporter des commentaires constructifs sur les questions de style), Mauricio Cepeda, Béatrice Cointe, Emmanuel Combet, Louis-Gaëtan Giraudet, Julien Lefevre, Elsa Mosseri, Marie-Laure Nauleau, Antonin Pottier, Philippe Roudier et Julie Rozenberg.

Je suis tenu de faire une mention spéciale au bureau le plus chaud (même durant l'hiver le plus froid (et le plus long : 11.2012 – 06.2013)), bravo à Baptiste Perrissin-Fabert et Raphaël Boroumand. Une pensée supplémentaire pour ceux qui m'ont soufflé l'idée de faire une thèse : Christine Patte, ma famille, et les directeurs d'étude de l'ENS.

Enfin et surtout, last but not least, je remercie Delphine Pernot qui m'a soutenu à bout de bras durant ces trois ans, à travers le meilleur et le pire, qui ne m'a jamais imaginé autrement qu'en futur docteur (ça a marché), et de qui je suis redevable d'une part substantielle de ce travail de longue haleine.

# TABLE DES MATIÈRES

# TABLE DES FIGURES

# LISTE DES TABLEAUX

# ACRONYMES

| | |
|---|---|
| LCOE | coût unitaire actualisé de l'électricité |
| CCS | carbon capture and storage |
| CDM | Clean Development Mechanism |
| CER | Certified Emissions Reduction |
| CIDD | Sustainable Development Tax Credit |
| CSPE | social contribution to electricity consumption |
| EE | energy efficiency |
| EEC | energy efficiency certificates |
| EPTZ | zero-rated eco-loan |
| ERU | emissions reduction unit |
| EU | European Union |
| EU-ETS | European Union Emission Trading System |
| FiT | feed-in tariff |
| GIEC | groupe intergouvernemental sur l'évolution du climat |
| GES | gaz à effet de serre |
| GHG | greenhouse gases |
| HCT | high-carbon technology |
| JI | joint implementation project |
| LBD | learning by doing |
| LCOE | levelized cost of electricity |
| LCT | low-carbon technology |
| MAC | marginal abatement cost |
| MACC | marginal abatement cost curve |
| MIC | marginal investment cost |
| MIRCC | marginal implicit rental cost of capital |
| REP | renewable energy power |
| RGGI | Regional Greenhouse Gases Initiative |
| RPS | Renewable Portfolio Standard |
| RT | thermal regulation |
| TGC | tradable green certificates |
| ZCT | zero-carbon technology |

# INTRODUCTION GÉNÉRALE

## LE BESOIN D'UNE TRANSITION ÉNERGÉTIQUE

La combustion d'énergies fossiles, au même titre que les changements d'usage des sols et certains procédés industriels, entraîne une augmentation des concentrations en gaz à effet de serre (GES) à l'origine d'un réchauffement climatique. Le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) relève ainsi dans son quatrième rapport (IPCC 2007) qu'entre 1970 et 2004, les émissions annuelles de GES ont augmenté de +70 %. Maintenir le réchauffement climatique en dessous de 2 °C va nécessiter de diviser par deux les émissions de GES mondiales d'ici à 2050. Cela n'est possible qu'en réduisant considérablement le recours aux énergies fossiles, qui représentent près de 82 % des émissions globales de GES en 2010 (Peters et al. 2012, IEA Statistics 2011).

La production d'électricité en représente à elle seule 34 % au niveau mondial, une part en hausse de près de 8 points depuis 2004. Au sein de l'Union Européenne (UE) également, en dépit d'une baisse continue depuis 1990 de l'intensité énergétique — calculée comme le rapport de l'énergie primaire consommée sur le produit intérieur brut (cf. la représentation de l'intensité énergétique des plus gros pays membres de l'UE sur la Figure 0.1) — la consommation d'électricité a crû sur toute cette période jusqu'à la crise économique de 2009 (cf. Figure 0.2).

La consommation d'électricité semble se stabiliser depuis 2009, mais la tendance à long terme reste soumise à des facteurs technologiques et économiques incertains. De nombreux scénarios de transition prévoient une hausse de la consommation d'électricité, entraînée par l'électrification de la mobilité, ou le développement de technologies de séquestration du carbone, relativement électro-intensives. [1]

De plus, pour les gouvernements, les enjeux d'une transition énergétique réussie vont au-delà du changement climatique. Ainsi qu'ils l'ont annoncé lors de communications récentes (DGEC 2013, EU 2011c), le Ministère français de l'environnement et la Commission européenne espèrent en effet atteindre d'autres objectifs en réduisant la consommation d'énergies émettrices de GES et en développant la consommation d'énergies décarbonées. Dans la promotion de la transition vers une production électrique décarbonée, lutter contre le changement climatique va ainsi de pair avec :

- combattre la précarité énergétique,
- réduire la dépendance énergétique,
- développer des technologies pour l'avenir et ainsi
- améliorer à long terme la compétitivité des industries locales et le pouvoir d'achat des ménages.

### *Réduire les émissions de GES du secteur électrique*

Réduire l'utilisation de sources d'énergies fossiles pour la production d'électricité est un défi à plusieurs titres. Les scénarios de décarbonisation du

1. Voir par exemple la *Roadmap 2050* de la Commission Européenne (EU 2011a;c), ou encore les scénarios d'Eurelectric (Eurelectric 2011) et de l'AIE (IEA 2012).

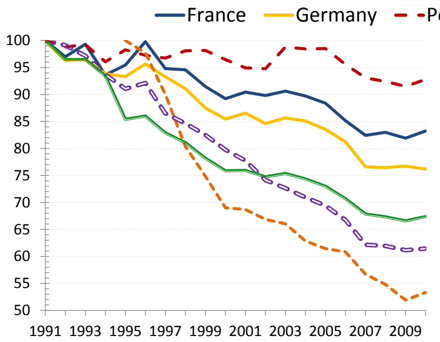



FIGURE 0.1: Intensité énergétique dans les plus gros pays membres de l'UE (indice 1991 = 100, sauf Pologne : indice 1995 = 100). Source : Eurostat (2013)

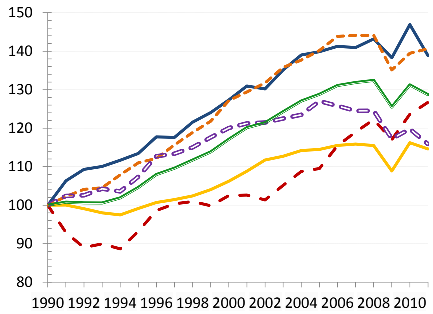



FIGURE 0.2: Consommation d'électricité dans les plus gros pays membres de l'UE (indice 1990 = 100). Source : Eurostat (2013)

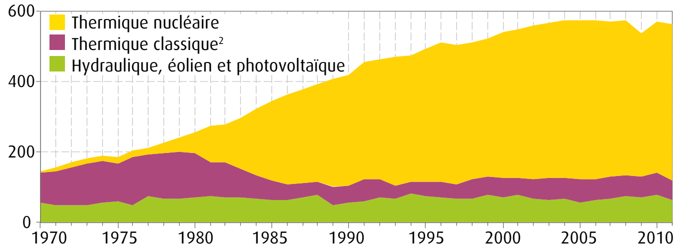
secteur électrique conduisent pour la plupart à une réduction quasi complète de ses émissions d'ici à 2050 [2], ce qui aura pour conséquence dans certains cas la fermeture de certaines centrales émettrices encore rentables en l'absence d'internalisation du coût du changement climatique. La France a ainsi fixé dans sa loi d'orientation de la politique énergétique (la loi POPE : Sénat 2005) un objectif de division par 4 de ses émissions d'ici 2050. Par ailleurs, les contraintes techniques de production et de distribution d'électricité nécessitent l'utilisation d'un bouquet de technologies diversifié, avec pour conséquence principale le fait qu'il n'existe pas de panacée, aucune technologie ne pourra apporter de solution seule.

En France, la production d'électricité est déjà en grande partie décarbonée (Figure 0.3a). En 2012, elle a été assurée à 76 % par le nucléaire, à 11 % par l'hydraulique, un peu moins de 10 % par le thermique classique, 2,7 % par l'éolien et 0,7 % par le photovoltaïque dont la part a presque doublé entre 2011 et 2012 (Louati et al. 2013). La production d'électricité ne représente ainsi que 15 % des émissions totale de GES (contre plus d'un quart au sein de l' UE-27).

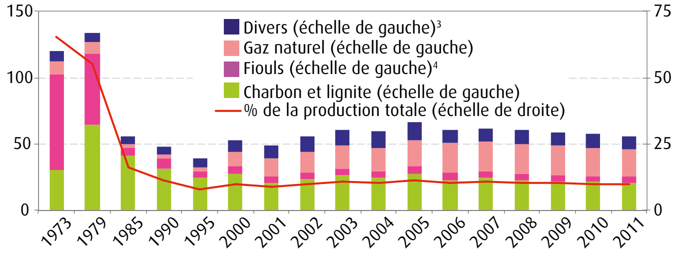
La proportion d'électricité produite à partir de sources fossiles n'a en revanche pas beaucoup évolué depuis les années 1980, oscillant autour de 11 % (cf. Figure 0.3b). Le portefeuille de technologies fossiles est varié, comprenant des centrales thermiques très émettrices (comme le fioul ou le charbon) et d'autres moins émettrices (comme le gaz). La part des énergies renouvelables est également restée relativement stable depuis les années 80 (cf. Figure 0.4). La production d'électricité renouvelable est principalement d'origine hydraulique, avec seulement un développement récent (bien que rapide) des sources éoliennes et solaires.

Au niveau européen les technologies fossiles tiennent une part nettement plus importante. Ainsi que le montre la Figure 0.5, chaque famille de combustible (solides, nucléaire, gaz et renouvelables) compte pour approximativement un quart de la production totale en 2010, avec une montée continue et importante du gaz depuis les années 90 (qui progresse de 7 % à 24 % entre 1990 et 2010), et une baisse plus faible du charbon et du pétrole (qui voient leur part baisser de respectivement 40 % à 25 % et 8 % à 3 % ). Le nucléaire reste lui relativement stable autour de 30 % tandis que les renouvelables progressent de 13 % à 21 %.

2. Voir la méta-analyse de Audoly et al. (forthcoming) ainsi que les scénarios référencés dans la note 1.




**(a)** Toutes technologies par groupes de technologies




**(b)** Technologies fossiles

FIGURE 0.3: Production d'électricité en France (en TWh). Tiré de SOES (2012).

*Un bouquet de technologies peu émettrices*

On le voit, l'atteinte des objectifs de réduction d'émission va nécessiter un développement accru de technologies peu ou pas carbonées : renouvelables, nucléaire, ou encore technologies d'efficacité énergétique, séquestration du carbone, ou bien technologies de stockage de l'électricité. Certaines technologies sont tout de même émettrices, mais à moindre niveau que la moyenne du portefeuille actuel. Ainsi, le remplacement des plus anciennes centrales au fioul ou au charbon par des centrales au gaz de dernière génération permettra de réduire les émissions globales de GES. Le champ des scénarios possibles de transition énergétique est large (Magne et al. 2010). Ils ne sont cependant pas tous équivalents.

Chaque technologie pose en effet des enjeux particuliers. Ainsi, de nombreuses technologies (comme les énergies renouvelables (ENR), la séquestration du carbone, le stockage de l'électricité) n'ont pas encore atteint leur pleine maturité et leurs coûts actuels, encore élevés, ne reflètent pas les réductions potentielles liées à la R&D et à l'apprentissage que leur développement pourrait générer. Le potentiel et la faisabilité d'autres technologies, comme la séquestration du carbone, ne font pas encore consensus. La contribution de ces technologies dans la production future d'électricité est incertaine et sujette à caution. D'autres technologies, dont certaines sont déjà très développées, suscitent des débats quant à leurs risques intrinsèques, tel le nucléaire depuis la catastrophe de Fukushima.

La plupart des technologies de substitution (les renouvelables, le nucléaire, ou bien encore les technologies de séquestration du carbone) ont des coûts fixes par MWh installé plus élevés que les centrales thermiques traditionnelles. Comme le montre la Commission Européenne dans les exercices de modélisation réalisés pour sa communication sur une transition vers une économie décarbonée (la *Roadmap 2050*, (EU 2011c)), passer d'un mode de production de l'énergie majoritairement fossile vers un mode majoritairement décarboné conduira ainsi à une hausse des coûts fixes et une baisse des coûts variables. Par ailleurs, de nombreuses technologies vont devoir être accompagnées d'investissements en infrastructure importants pour ré-

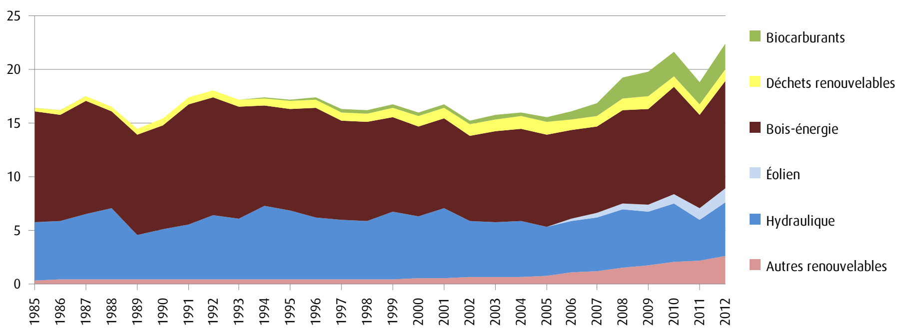



FIGURE 0.4: Production d'énergie primaire en France à partir de technologies renouvelables thermiques (bois énergie, déchets, biocarburants) et électriques (éolien, solaire, hydraulique), en tonnes équivalent pétrole. Tiré de Louati et al. (2013).

véler leur plein potentiel. À terme, cela pourrait signifier un système énergétique moins coûteux, mais cela exacerbe également temporairement le besoin en capitaux pour financer cette transition, dans un contexte de crise économique.

Le maintien de la fiabilité de la fourniture d'électricité va nécessiter de panacher les investissements réalisés. La plupart des technologies décarbonées sont moins flexibles ou moins fiables que les technologies fossiles existantes. Le nucléaire ne peut s'adapter à la puissance appelée aussi rapidement que d'autres technologies. Certaines technologies renouvelables (éolien, solaire) sont dépendantes de contingences climatiques, produisent de l'électricité de manière intermittente et parfois difficilement prévisible. La gestion de cette intermittence va devenir problématique avec l'augmentation de la part de technologies peu flexibles dans le portefeuille de production et va générer des besoins de réserves. Bien que certaines technologies renouvelables répondent aux critères de fiabilité et de flexibilité pour sécuriser le système électrique (comme l'hydraulique, la biomasse) ou que d'autres technologies non émettrices permettraient d'atteindre le même résultat (stockage de l'électricité ou du carbone), aucune ne possède le potentiel nécessaire pour répondre à toutes les situations au niveau européen.

*Des contraintes dynamiques fortes*

Le secteur électrique est fortement capitalistique. Quelles que soient les technologies choisies, toute transformation implique des investissements importants en capacités de production, de transport, de distribution et de consommation. La transition énergétique ne peut se faire que sur une échelle de temps conséquente, en prenant en compte l'inertie liée à l'accumulation du capital ainsi que les divers effets d'apprentissage, effets d'échelle et valeurs d'option générés dans le temps. L'électricité est un bien non stockable (en l'état actuel des technologies ou à des coûts prohibitifs) et essentiel, ce qui signifie que la production doit être en constante adéquation avec une demande parfois très variable. L'intermittence des renouvelables, qui ont une priorité d'accès au réseau, accentue ce problème.

Cette thèse va se concentrer sur une partie de ces problèmes, laissant d'importantes questions de côté pour des recherches ultérieures. Nous nous intéresserons aux stratégies à mettre en place pour atteindre les objectifs de réduction d'émissions dans le secteur électrique tout en tenant compte de

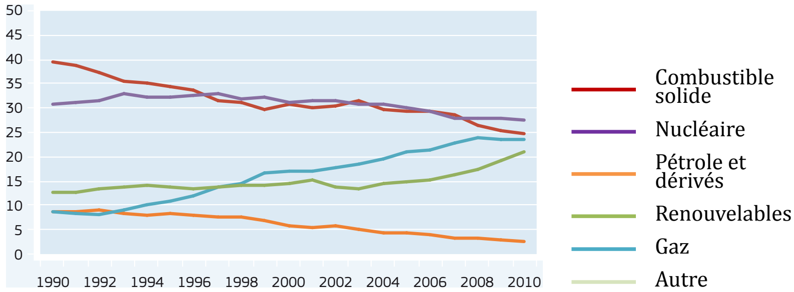



**Figure 0.5**: Part en % de l'électricité par type de combustible dans l'Union Européenne. Tiré de EU (2012).

ces diverses contraintes.[3] Pour mener à bien une transition énergétique, il faudra en effet arbitrer entre coûts à court terme et bénéfices à long terme, tout en garantissant l'équilibre entre technologies et satisfaction de la demande, sans chercher à imposer une solution technique unique.

## LE CHOIX D'UN PORTEFEUILLE DE POLITIQUES

### *Donner une valeur aux émissions de GES*

Un enjeu majeur de la transition vers une économie décarbonée — quels que soient les secteurs considérés — est l'internalisation des dommages liés aux changements climatiques dans les comportements de consommation et d'investissement des agents. La théorie économique prédit que dans un cadre idéal,[4] la manière la moins coûteuse d'atteindre une cible donnée de réduction d'émissions est de donner une valeur aux émissions de GES, correspondant aux dommages marginaux, afin de décentraliser au niveau des entreprises les décisions d'investissement dans les technologies bas-carbone, sous la forme d'une taxe pigouvienne (Pigou 1920). Dans un tel cadre, toute mesure supplémentaire visant à réduire les émissions de GES augmenterait ainsi les coûts pour la société.

En l'absence de coûts de transactions et en dans un cadre certain, cette taxe pigouvienne est équivalente à la détermination de droits de propriété sur la pollution, en l'occurrence des droits d'émissions de GES, d'après le théorème de Coase (Coase 1960). Ces droits à polluer, en étant ensuite directement échangés entre les agents (pollueur ou simple consommateur victime de la pollution), éviteraient ainsi une intervention publique qui serait

3. L'ensemble des chapitres considèrent une contrainte sur les émissions du secteur électrique, ainsi qu'une contrainte de satisfaction instantanée de la demande. Le Chapitre 3 traite en outre de diverses problématiques liées aux contraintes dynamiques d'investissement et de production. Nous laissons de côté deux mécanismes très structurants dans les problématiques d'investissement au sein du secteur électrique : les effets d'apprentissage, déjà largement traités dans la littérature (cf. ci-dessous), ainsi que les problèmes liés à l'intermittence des technologies renouvelables, encore peu traités mais qui nécessitent un bagage méthodologique spécifique (cf. la revue de littérature et la discussion faite par Ambec and Crampes (2012)).

4. Ce cadre idéal suppose une concurrence pure et parfaite (soit atomicité des agents, homogénéité des produits, transparence de l'information, libre entrée et sortie sur le marché, libre circulation des facteurs de production) sur les différents marchés considérés, et en particulier les marchés électriques. Ces derniers sont pourtant notoirement enclins aux pouvoirs de marché David and Wen (2001). Cette thèse se focalise sur des questions de politique environnementale optimale, et laisse de côté de telles questions pourtant centrales. Ce cadre idéal suppose également l'absence de défaillances et d'externalités supplémentaires, comme il sera discuté plus loin, ainsi que l'absence d'incertitude, comme le montre le Chapitre 2.

coûteuse et incertaine en cas de mauvaise anticipation du niveau de dommage marginal. Un marché efficace de permis d'émissions, où l'ensemble des agents serait prêt à révéler son estimation privée de la valeur des dommages environnementaux liés aux émissions de GES paraît en revanche peu crédible, tant les coûts de transaction sont en réalité élevés lorsque les agents sont nombreux et atomisés. Le marché de permis d'émissions mis en place par l'UE (European Union Emission Trading System (EU-ETS) en anglais), décrit dans le Chapitre 4, s'en rapproche, mais pour un nombre d'acteurs restreint aux plus gros émetteurs industriels.

Cette valeur du carbone, signalée via une taxe ou via un prix issu d'un marché de permis d'émissions, devrait permettre de réduire les émissions de GES par trois canaux (Neuhoff 2008) :

- L'accroissement du coût des ressources les plus carbonées (énergie ou biens intermédiaires) incite à une réduction de leur utilisation au profit de ressources moins polluantes, à capacité de production égale (le *fuel-switch*).
- La meilleure rentabilité de technologies peu émettrices incite à investir et à utiliser des options qui ne seraient pas rentables en absence de signal sur la valeur des émissions évitées.
- L'anticipation de la contrainte future sur les émissions de GES incite à réaliser des investissements supplémentaires en R&D, permettant l'émergence de nouvelles technologies bas-carbone.

Une autre possibilité d'action des pouvoirs publics pourrait consister en une régulation directe des usages ou bien en une interdiction pure et simple des technologies les plus polluantes. Mais avec une telle approche, le régulateur serait contraint de gérer les émissions et donc les niveaux de production d'une grande partie de l'économie, et de maîtriser tous les aspects de l'utilisation d'énergies carbonées. La mise en place d'un grand nombre de telles contraintes est contraire au principe de libéralisation des marchés préconisée par l'UE. Elle paraît de plus illusoire, si on considère que c'est au niveau des entreprises et des agents économiques que se trouve la connaissance fine des gains d'efficacité potentiels.

### *Combiner des instruments de politique climat-énergie*

Les écarts au cadre idéal évoqué précédemment sont nombreux, créant autant de situations où l'allocation des ressources n'est pas optimale. La présence d'externalités d'apprentissage peut conduire à un sous-investissement en recherche ou en capacité de production. Un pan très riche de la littérature économique est consacré à la problématique de cette double défaillance de marché : le changement climatique et le défaut d'appropriation des pleins bénéfices issus d'investissements en recherche ou en déploiement de technologies immatures (Fischer et al. 2003, Jaffe et al. 2005). La présence de cette défaillance supplémentaire nuit au bon développement des technologies bas-carbone, même en présence d'un signal-prix sur les émissions de GES. Cela justifie la mise en place de subventions pour la recherche et le déploiement de telles technologies (voir par exemple Popp et al. (2009) ou Stavins et al. (2004)). La présence d'effets d'apprentissage et l'innovation influent sur les trajectoires optimales de transition, en rendant des investissements précoces plus favorables ou au contraire plus coûteux, selon le type d'externalité d'apprentissage considéré (voir par exemple l'analyse de Goulder and Mathai (2000)).

Les défaillances des marchés de permis d'émission ou de l'électricité, comme le manque d'information dont disposent les ménages sur le coût de leur consommation pour la société (Jaffe et al. 2004), peuvent pervertir les décisions de production et d'investissement. Les problèmes principal-agent peuvent avoir le même effet pour les investissements d'efficacité énergétique (Gillingham et al. 2012) et peuvent empêcher la réalisation du potentiel existant et rentable de réduction d'émissions et de gains d'efficacité. Ces défaillances constituent autant de justifications pour une action correctrice de la part du régulateur.

L'ensemble des pays membres de l'UE ont mis en place des portefeuilles de mesures visant à la fois à réguler l'offre et la demande d'énergie, afin d'atteindre leurs objectifs de politique climatique ainsi que d'autres gains attendus de la transition énergétique comme la sécurité énergétique ou le développement économique. L'UE a de ce fait annoncé en 2008 la stratégie du « 3×20 », projetant la baisse des émissions de GES et de la consommation d'énergie de 20 % et l'augmentation de la part d'ENR à 20 % de la production totale d'énergie d'ici 2020 (EU 2008a;b; 2011b). Au marché de permis d'émissions mis en place au niveau européen s'ajoute un ensemble de mesures visant à réguler les marchés de l'énergie, à développer les ENR, à promouvoir l'efficacité énergétique (EE), à réorienter l'innovation en général ainsi qu'un cadre de coopération pour développer des infrastructures de grande taille (CPI 2013).

*Atteindre les cibles climatiques de long terme*

Les obstacles à l'arrivée de nouvelles technologies ou à l'entrée de nouveaux producteurs d'électricité, ou bien encore les difficultés d'accès aux capitaux peuvent empêcher l'émergence de nouvelles technologies prometteuses, et peuvent faire obstacle aux investissements stratégiques nécessaires pour l'atteinte des potentiels de long terme des technologies les plus capitalistiques. Les renouvelables auront ainsi plus de valeur (au niveau social) si plusieurs technologies avec des sources différentes, ou bien plusieurs régions ayant des fluctuations décorrélées, sont utilisées (Nagl et al. 2013). Des technologies d'information auprès des consommateurs, ou bien d'optimisation du réseau comme les compteurs intelligents, n'auront d'impact que si elles sont déployées pour une part suffisante du marché.[5] L'atteinte des objectifs annoncés par l'UE et la France est ainsi incertaine. La part de renouvelables en 2010 était juste en dessous de l'objectif annoncé. De la même façon, réduire la consommation finale d'énergie en France de 1,5 % par an, notamment en rénovant 500 000 bâtiments par an, paraît très ambitieux.

L'accumulation de capital et l'accumulation des émissions dans l'atmosphère induisent des inerties dont il faut tenir compte dans la détermination des trajectoires d'investissement et de production. En particulier, des effets de congestion dans les investissements dans des technologies particulières doivent être pris en compte pour déterminer la trajectoire optimale d'investissement. La représentation de ces effets dans les modèles d'investissement du secteur électrique en est à ses balbutiements, se résumant pour l'heure en de simples bornes sur les vitesses d'investissement dans les modèles numériques (voir par exemple le modèle MARKAL : (Fishbone and Abilock 1981, Loulou 2008)).

5. Un livre de Grubb, Hourcade and Neuhoff à paraître détaille ces différents piliers de l'action publique (Grubb et al. 2014).

*Anticiper les effets de l'incertitude*

L'incertitude qui pèse sur plusieurs variables clés de décision, des dommages dus au changement climatique au niveau de croissance économique en passant par le développement de technologies zéro carbone, complique encore la détermination du portefeuille optimal d'instruments pour réduire les émissions de GES. L'article de Weitzman (1974) a initié une vaste littérature sur les mérites comparés d'instruments fondés sur les prix, sur les quantités ou mixtes, en fonction du type et du degré d'incertitude considérés.[6] Le marché de permis d'émission Européen est le fruit de ces recherches, un instrument hybride qui combine des caractéristiques d'instrument prix et quantité (Convery 2009), mais dont l'efficacité reste sensible à plusieurs facteurs incertains.

Les instruments des politiques climat-énergie sont ainsi sensibles au contexte économique. L'incertitude régulatoire et économique qui pèse sur les industries fortement émettrices (donc les plus sujettes à la régulation environnementale) réduit l'efficacité des instruments en place, en accroissant le risque — donc le coût, des investissements bas-carbone encore à réaliser (Durand-Lasserve et al. 2011). Le prix des permis d'émissions s'est effondré sous l'effet conjugué de la récession économique et des déclarations de politiques contraignantes pour les ENR et l'EE (Neuhoff et al. 2012), ce qui fait craindre la non-atteinte des objectifs de réduction de GES dans les temps.

L'incertitude sur le niveau de production des technologies renouvelables intermittentes constitue un autre élément influant sur l'efficacité d'un portefeuille donné d'instruments de politique climat-énergie. Ambec and Crampes (2012) montrent ainsi que les rigidités actuelles des marchés électriques (prix régulés, priorités d'accès au réseau) vont empêcher la mise en place d'un portefeuille de production efficace si des instruments adaptés ne sont pas mis en place.[7]

## MOTIVATIONS ET QUESTIONS DE RECHERCHE

Cette thèse s'intéresse au choix et à l'efficacité des portefeuilles d'instruments de politique climat-énergie mis en place pour assurer une transition vers un secteur électrique décarboné. Elle étudie ces questions en développant des outils de modélisation adaptés, et s'organise autour de quatre chapitres relativement autonomes, mais dont les problématiques sont liées. La thèse s'articule ainsi autour de cinq questions de recherche transversales principales.

*Un prix du carbone est-il suffisant pour déclencher une transition décarbonée, dans un cadre incertain et dynamique ?*

La littérature décrit déjà un certain nombre de circonstances dans lesquelles le signal-prix du carbone est défaillant (présence d'externalités multiples, biais cognitifs, etc.). Les défaillances découlant de la prise en compte d'une incertitude importante du niveau de la demande d'énergie (entraînant un

6. Voir par exemple Ambec and Coria (2012), Creti and Sanin Vázquez (2011), Hepburn (2006), Hoel (2012), Kalkuhl and Edenhofer (2010), Mandell (2008), Quirion (2005).

7. Ce problème, bien que central dans la détermination d'un portefeuille de politiques cherchant à atteindre un niveau conséquent de production décarboné, ne sera pas traité dans cette thèse. Il nécessite l'élaboration et l'utilisation d'outils spécifiques, et ne peut être correctement représenté au moyen des modèles développés dans cette thèse. Cette question pourrait cependant faire l'objet d'extensions intéressantes des chapitres existants.

risque de prix nul du carbone) et de la prise en compte d'effets de congestion dans les investissements du secteur électrique font cependant encore défaut dans la littérature existante. Ces éléments constituent-ils des défaillances supplémentaires ? Quel est leur impact sur le signal-prix carbone ? En leur présence, le signal-prix du carbone assure-t-il une trajectoire optimale d'investissement dans les technologies de réduction d'émission ?

*La mise en place d'instruments additionnels de promotion de technologies de réduction d'émissions est-elle justifiée par les défaillances du prix du carbone ?*

De multiples défaillances du prix du carbone, déjà bien identifiées dans la littérature, justifient la mise en place d'instruments supplémentaires destinés à les corriger. Dans quelle mesure les défaillances identifiées dans cette thèse — une incertitude importante sur la demande d'électricité et la présence d'effets de congestion sur les investissements — peuvent-elles être corrigées par des instruments de promotion des renouvelables et de l'efficacité énergétique ajoutés au prix du carbone ? En d'autres termes, ces défaillances justifient-elles la mise en place d'instruments spécifiques comme un tarif d'achat renouvelable ou une aide à l'investissement en capital efficace ?

*Quels sont les impacts des instruments de promotion de technologies de réduction d'émissions ajoutés au prix du carbone ?*

De fait, les États déploient déjà un portefeuille d'instruments incluant des instruments de promotion des renouvelables et de l'efficacité énergétique pour atteindre leurs objectifs de lutte contre le changement climatique. Ces instruments interagissent via les marchés électriques et le marché de permis d'émissions. Quels sont les impacts de ces instruments additionnels sur le signal-prix du carbone ? Quels sont leurs effets sur les variables clés du système, tel que le prix à la consommation d'électricité ? Provoquent-ils des transferts spécifiques de surplus entre agents, et leurs interactions ont-ils des effets négatifs sur le bien-être social (défini ici comme l'agrégation du surplus des consommateurs et des producteurs) ?

*Quelle est l'efficacité d'un portefeuille donné incluant des instruments de promotion des renouvelables et de l'efficacité énergétique pour réduire les émissions de GES à long terme ?*

Une fois les interactions entre instruments de politiques climat-énergie et leurs effets sur les défaillances du prix du carbone identifiés, peut-on caractériser l'efficacité générale d'un portefeuille donné incluant un prix du carbone et des instruments de promotion des renouvelables et de l'efficacité énergétique pour atteindre une cible de réduction d'émissions ambitieuse et durable ?

*La France peut-elle se s'affranchir d'une partie de ses instruments ?*

Étant donné le portefeuille français actuel d'instruments de politique climat-énergie, et son efficacité au regard d'un objectif ambitieux de long terme, les instruments le composant y ont-ils tous leur place ? Quels sont les instruments les moins adaptés aux enjeux auxquels la politique climat-énergie française va devoir faire face à l'avenir ?

## PLAN ET APPORTS DE LA THÈSE

La thèse s'articule autour de quatre chapitres relativement autonomes présentant une question de recherche originale. Chacun développe une méthodologie propre pour y répondre.

1. LE PREMIER CHAPITRE étudie l'efficacité d'une combinaison d'instruments et l'influence d'une telle combinaison sur le signal-prix du carbone. Il étudie les interactions ayant lieu entre un plafond d'émission (type EU-ETS), un tarif d'achat renouvelable financé par une taxe à la consommation d'électricité (type CSPE) et une subvention à l'efficacité énergétique sur le prix de l'électricité au consommateur, le prix du carbone ainsi que le bien-être social [8] et les transferts entre agents. Un modèle analytique d'équilibre statique du secteur électrique est développé, décrivant de manière explicite les coefficients de variation des variables endogènes (prix et productions d'électricité) en fonction des changements dans les instruments de politique climat-énergie. Il est montré que :

- Pour un tel portefeuille d'instruments, très courant au sein des pays de l'UE (il mime en autres la situation de la France, de l'Allemagne, de l'Italie), l'ajout ou l'augmentation du tarif d'achat de l'électricité d'origine renouvelable diminue le prix à la consommation de l'électricité, et ce en dépit du fait que la taxe à la consommation augmente. Ce résultat tient lorsqu'on peut faire l'hypothèse que la production d'électricité non renouvelable est indépendante du prix du carbone. Cela est en particulier faux si on considère plusieurs technologies de production non-renouvelable avec des intensités d'émissions différentes (par exemple s'il y a beaucoup de nucléaire) ou si on considère la possibilité d'améliorations de l'efficacité d'émission de la technologie fossile.
- L'ajout d'un tarif d'achat provoque un transfert de la rente carbone vers les consommateurs et les producteurs renouvelables. Lorsque les permis d'émissions sont mis aux enchères, le profit des producteurs fossiles est inchangé par le tarif. Lorsque les permis sont distribués gratuitement, leur profit diminue du montant du transfert.
- La rente carbone suit une courbe en U en fonction du plafond d'émissions : pour des plafonds relativement bas l'augmentation du plafond augmente la rente carbone, tandis que l'inverse est vrai pour des valeurs relativement élevées du plafond.

2. LE DEUXIÈME CHAPITRE s'intéresse au choix optimal d'instruments dans une situation contrainte où le régulateur ne peut choisir qu'au sein d'un portefeuille limité incluant un plafond d'émissions (type EU-ETS) et une subvention renouvelable. Le chapitre cherche à apporter une justification à la combinaison de plusieurs instruments pour réduire les émissions du secteur électrique lorsque le niveau des coûts de réduction d'émissions est très incertain. Un modèle analytique du secteur électrique avec incertitude sur le niveau de demande future est développé, avec une application numérique au secteur électrique européen, contenant une analyse de sensibilité. Il est montré que :

- Lorsque l'incertitude sur la demande future d'électricité est suffisamment élevée, le risque d'un prix du carbone résultant de l'équilibre offre-demande sur le marché de permis d'émissions égal à zéro ne peut être écarté. Dans ces circonstances, un portefeuille d'instruments incluant une subvention ENR est

8. Défini ici comme l'agrégation du surplus des consommateurs et des producteurs.

plus performant qu'un plafond d'émission seul pour réduire les émissions de GES. En d'autres termes, le prix du carbone ne suffit pas à garantir un niveau suffisant de réductions d'émissions.

- Les résultats numériques montrent que pour un ensemble raisonnable de paramètres, l'ajout d'une subvention ENR de l'ordre de 3 à 10 €/MWh peut augmenter le bien-être social d'une dizaine à plusieurs centaines de millions d'euros par an.

3. LE TROISIÈME CHAPITRE examine la question de l'efficacité du signal-prix carbone pour entraîner une transition vers une économie bas-carbone dans un cadre dynamique. Un modèle analytique en temps continu du secteur électrique est développé, où les centrales à charbon existantes, très émettrices de GES, peuvent être remplacées par du gaz de dernière génération (partiellement décarboné) ou des renouvelables (totalement décarbonées). La production électrique est soumise à une contrainte de demande instantanée ainsi qu'à une contrainte de politique climatique intertemporelle, représentée par un plafond sur les émissions cumulées. Des effets de congestion sur les investissements sont représentés sous la forme de coûts convexes. Il est montré que :

- La prise en compte de l'inertie induite par l'accumulation de capital et par les coûts convexes d'investissement conduisent à un résultat qui peut paraître contre-intuitif : sur la trajectoire optimale de transition, la technologie zéro carbone (par exemple les ENR) est toujours construite à un coût plus élevé que la technologie bas-carbone (par exemple le gaz), même en internalisant la contrainte climatique au moyen d'un prix du $CO_2$.
- Les investissements zéro carbone peuvent commencer avant les investissements bas-carbone, même si ces derniers sont moins chers par tonne de $CO_2$ évitée.
- La transition optimale vers un secteur électrique bas-carbone impose d'investir dans des centrales à gaz qui pourront être sous-utilisées par la suite.
- Le signal-prix carbone doit être assorti d'une cible de long terme pour permettre une anticipation parfaite de la trajectoire d'investissement optimale.

Une simulation numérique calibrée sur le secteur électrique européen est également réalisée. Il est montré que pour le secteur électrique européen, le coût unitaire actualisé de l'électricité (LCOE) optimal est supérieur pour l'éolien que pour le gaz. Cela suggère que le classement des technologies par leur LCOE (ainsi qu'il est fait dans de nombreux manuels) induirait un surplus d'investissements dans les centrales à gaz par rapport à l'optimum social.

4. LE QUATRIÈME ET DERNIER CHAPITRE dresse un bilan qualitatif des instruments des politiques climat-énergie déployés en France. Après un bref panorama historique de quarante années de politiques climat-énergie en France, ce chapitre fat une revue de la littérature sur l'efficacité de chaque instrument pris isolément. Une évaluation qualitative de l'efficacité du portefeuille pris dans son ensemble est ensuite réalisée. Il est montré que :

- Tant que le prix du carbone reste bas, peu d'effets d'interactions sont à craindre avec les autres instruments du portefeuille climat-énergie, d'autant moins que de nombreuses défaillances du marché de l'électricité empêchent la diffusion du signal-prix carbone aux consommateurs d'électricité.
- L'existence de ces défaillances, ainsi que des effets de congestion dans les investissements en technologies de réduction d'émissions et l'incertitude qui pèse sur l'évolution du signal-prix du carbone justifient le maintien d'un portefeuille contenant plusieurs instruments.

- La composition exacte de ce portefeuille dépend en revanche des hypothèses sur la trajectoire du signal-prix du carbone. La nature des interactions qui pourraient être générées par une hausse de ce signal-prix vont de plus dépendre de la nature de l'instrument qui le produira : nouvelle taxe liée au contenu carboné de l'électricité ou bien retrait définitif de permis d'émissions. Dans le premier cas, les interactions seraient bien moindres et un portefeuille plus étoffé pourrait se justifier.
- Dans l'éventualité d'une contribution climat-énergie significative en 2015 (comme projeté par le gouvernement actuel), ou bien si les États-membres de l'UE parviennent à se mettre d'accord sur une réforme d'envergure de l'EU-ETS, certains instruments faisant la promotion de réduction de consommation dans le résidentiel ou le tertiaire pourraient se révéler superflus. Un instrument unifié donnant les moyens aux particuliers de réaliser des rénovations d'envergure du bâti existant pourrait remplacer une partie des instruments actuels de promotion de l'efficacité énergétique.
- Dans l'éventualité d'un signal-prix du carbone durablement faible, des niveaux plus élevés de subvention pour ces technologies d'efficacité énergétique et de production d'électricité à partir de renouvelables pourraient se justifier.

La conclusion générale synthétise les résultats des quatre chapitres et répond aux questions posées plus haut, avant de proposer quelques éléments d'ouverture.

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# 1 COMBINING TARIFFS FOR RENEWABLES AND EMISSION CAP: DOES IT REDUCE THE ELECTRICITY PRICE? [1]

## 1.1 INTRODUCTION

In virtually all member states of the European Union (EU), the electricity sector faces a multiplicity of climate and energy policy instruments. Most EU member states promote electricity generation from renewable sources through feed-in tariffs (FiTs), which guarantee a given level of remuneration for production from renewable sources, while others implemented quantity mandates such as tradable green certificates (TGC) and Renewable Portfolio Standard (RPS) (Ragwitz et al. 2007, EU 2009d). TGC and RPS require a certain percentage of total electricity production to come from renewables. Producers are awarded green certificates when they produce renewable electricity. Electricity suppliers can comply to their renewable target by purchasing enough certificates. [2]

Moreover, GHG emissions from fossil-fueled electricity production facilities are capped across the EU. In the European Union Emission Trading System (EU-ETS) member states auction emission allowances that are later exchanged through an allowance markets among electricity plants and carbon-intensive facilities in other industrial sectors (EU 2009a;c). On the demand side, the main instrument for energy efficiency promotion are in general fiscal incentives, but energy efficiency labels on appliances (EU 2009b) and energy efficiency obligations (Giraudet et al. 2012, Lees 2012) are also used.

The EU-ETS aims at reducing emissions from carbon-intensive industries in a cost-effective way (EU 2009c, p. L140/63). While renewables and energy savings are also primarily a part of the package needed to comply with the Kyoto Protocol, several other rationales have been used to justify these additional measures. In particular, the renewables Directive from the European Parliament and Council states that renewables

> "have an important part to play in promoting the security of energy supply, promoting technological development and innovation and providing opportunities for employment and regional development" (EU 2009d, p. L140/16).

Comparable arguments have been raised for energy savings incentives, along with arguments on the burden of energy expenses on households and the evolution of the electricity price.

The European Climate and Energy Package has indeed been thought to complement the long-lasting objective of liberalizing the European energy markets. In this view,

> "support schemes for renewables [...] were introduced on the grounds of incomplete market opening [and] incomplete inter-

1. This chapter stems from an extended version of the model published as Lecuyer and Bibas (2011).

2. See also IEA (2010a;b;c) for policies and measures databases across the EU among other countries, as well as RES-LEGAL (2010) for a comprehensive description of legal source on European renewables promotion schemes.

> nalization of the external costs of conventional generation" (EU 2012, p. 14),

with the idea that increased competition would bring decreasing electricity prices.

These overlapping policy instruments are however prone to interactions through electricity and environmental commodities markets, leading to far from obvious effects on the consumer electricity price that depend on the actual policy mix. While renewable technologies tend to reduce the market price of electricity through reduced variable costs and priority access to the grid, most of European member states finance their renewables promotion scheme through taxes on the consumption of electricity, which tend to increase the consumer price. Moreover, when renewables and energy savings promotion schemes are combined with an EU-ETS, they can reduce the electricity price by easing the emission constraint, and thus lowering the carbon price that is passed through to consumers.

The objective of this chapter is to detail the mechanisms at play and to investigate the outcome of these interactions on the electricity consumer price and on the welfare when a policy mix featuring the policy instruments most used in European countries is considered. These include a cap on emissions from the electricity sector, FiTs for renewables, the tax on electricity consumption needed to finance this renewable promotion scheme, and subsidies for energy efficiency.

By using a simple analytical equilibrium model of supply and demand in the electricity sector featuring these policy instruments, I find that when a FiT financed by a tax on electricity consumption is combined with a cap on the emissions from electricity production, increasing the FiT will decrease the consumer price, because the electricity production expands and the equilibrium shifts toward smaller consumer prices along the downward sloping demand curve. Raising the FiT increases the tax to finance it, and thus the consumer price, but the decrease in the carbon price and the wholesale electricity price following the reduced marginal abatement cost is stronger. This remains true with a subsidy for energy efficiency, but holds only if the fossil production can be assumed fixed by the emission cap. In particular, considering several non-renewable technologies with very different emission rates (e.g. with nuclear production) or the possibility of efficiency investments in the fossil production plants would alter the results and would be an promising avenue for further research.

The subsidy for energy efficiency interacts with the FiT in an asymmetric way. While the subsidy promotes efficiency to the detriment of sufficiency behaviors, the FiT on the opposite reduces both sufficiency and efficiency behaviors. I find moreover that tightening the cap has an ambiguous effect on the consumer tax and more surprisingly on the carbon price, due two countervailing effects. On the one hand, tightening the cap decreases the total electricity production, thus rising proportionally the tax needed to finance an unchanged quantity of renewables, and therefore the marginal abatement costs. On the other hand, substitutions with investment in energy efficiency tends to reduce the marginal abatement costs. This can lead in extreme and unlikely situations to an increase of both the emission cap and the carbon price when supply and demand are very elastic.

Adding a FiT decreases the total welfare if the subsidy for energy efficiency is low enough. It also causes a transfer from the carbon rent to consumers and renewable producers, raising their surpluses. It however leaves the profit from fossil production unchanged if allowances are auctioned.

Despite being widely observed in empirical studies, analytical studies disagree on the mechanisms behind this result. Section 1.2 reviews this literature, disentangling the interactions effects between the various policy instruments considered and the importance of several assumptions made. The analytical literature primarily focus on simpler policy mixes, either including only a renewable promotion scheme or considering a constant exogenous carbon price. These studies thereby overlook one specific interaction effect between the emission cap and the FiT, namely the decrease in the carbon price induced both by the FiT and by the tax necessary to finance it. They moreover do not address the interaction effects with promotion instruments for energy efficiency.

Section 1.3 presents the setting and equations of the model, as well as the policy instruments featured and the welfare function. Section 1.4 then discusses the interaction effects on electricity prices by computing the total differentials of the endogenous variables of the system, and presents the main analytical results. Section 1.5 discusses the results and concludes.

## 1.2 INTERACTIONS EFFECTS ON THE ELECTRICITY PRICE: A REVIEW

The literature disagrees about the final outcome of combining renewable promotion mechanisms and emission reduction instruments on the electricity price. As a result, the final effects on the consumer surplus is also unclear. In a numerical model of the European electricity sector including a cap on emissions and FiTs for renewables, Böhringer and Rosendahl (2009) predict a reduced consumer price when adding or increasing the FiT. Empirical studies by Sensfuß et al. (2008) and de Miera et al. (2008) analyzing electricity and emission allowance market data find that the German and the Spanish FiTs decreased consumer electricity prices. Meanwhile, Jonghe et al. (2009), Traber and Kemfert (2009) both anticipate a price increase, using numerical models. Most studies conclude however that the final effect on the consumer price is indeterminate and depends on the relative stringency of the renewable market share and the emission cap and on parameters of electricity supply functions (see e.g. Jensen and Skytte (2003) and Unger and Ahlgren (2005)).

This discrepancy is the result of several countervailing effects depending on the policy mix. Following sections will review and disentangle those effects, by considering successively the policy mixes modeled, in increasing order of complexity. While in isolation, a subsidy on renewables and a price on carbon will obviously enough respectively decrease or increase the electricity market price, when considered together, or when an endogenous financing mechanism is considered, results may vary.

### 1.2.1 Subsidy for renewables alone: illustrating the merit order effect

Setting a subsidy for renewables in isolation directly affects the electricity market price through the *merit order effect*. Because of zero variable costs and a priority access to the grid, the additional renewable production incentivized by the subsidy displaces electricity produced by thermal-based conventional technologies, and shifts the merit order curve. This sometimes leads to the displacement of the marginal technology, which would have set the price in the spot market, by a technology with lower variable costs. In the long run, renewable subsidies will reduce the long term costs of renewables, leading to more and more substitutions away from thermal-based generation, and the market price of electricity tends to decrease.[3] Using real-world data, Sensfuß et al. (2008) and de Miera et al. (2008) describe in great detail this effect and find that the German and the Spanish FiTs indeed decreased consumer electricity prices in 2006 (including the tax paid by consumers to finance the support scheme, see the discussion below).

### 1.2.2 Incentive for emission reduction alone: illustrating the carbon cost pass through

Introducing a constraint on emissions or a tax on the emissions from the electricity sector[4] increases the marginal production cost of electricity from fossil fuel. This increase may then be passed through to consumers, and increase the consumer electricity price, in an effect that we shall label the *cost pass through effect*. In this chapter, we will assume a 100 % cost pass through, but it may vary according to the market structure or the degree of competition.[5]

### 1.2.3 Combining a subsidy for renewables and an endogenous financing mechanism

Fischer (2010) discusses the effects of a RPS on electricity prices. As argued by Fischer, and in a setting with no uncertainty, a RPS is formally equivalent to the combination of an implicit subsidy on renewables (decreasing the electricity price through the merit order effect) and an implicit tax on fossil production set to finance the subsidy (increasing the consumer price in a mechanism similar to the cost pass through effect). According to her findings, the final outcome on the consumer electricity price of a combining a subsidy for renewables and an endogenous financing mechanism depends on the relative elasticities of the supply functions, and the market share of renewables, since the implicit tax level depends both on the level of the subsidy and on the quantity of renewables.

If renewable supply is sufficiently elastic and the renewable market share relatively low, the merit order effect exceeds the effect of the increasing tax on the consumer price. In other terms, the RPS acts more as a subsidy for renewables producers than as a tax on fossil production, or as Fischer expresses it:

> "models are more likely to predict that RPSs will produce lower consumer electricity prices when they embed rigidities in natural gas supply, assume that large portions of nonrenewable generation are fixed, parameterize relatively flat marginal costs for renewables, or target modest increases" (Fischer 2010, p. 97).

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3. We ignore here learning effects that also influence the marginal cost of renewables in the long run. Such effects would however further decrease the marginal cost, amplifying possible effects of an increasing renewable production subsidy.

4. Such a tax is equivalent to a tax on fossil fuel or on electricity production from fossil fuel when only one polluting technology is considered, as is the case in (Fischer 2010) or in this chapter.

5. A discussion of consequences of imperfect competition is beyond the scope of this chapter. See for instance Fell et al. (2013) for a recent discussion of carbon costs pass through in electricity markets.

As without uncertainty, a setting including a subsidy or FiT financed by an endogenous tax on consumption is analytically comparable to a RPS, these results sheds light on the findings of Jonghe et al. (2009) and Jensen and Skytte (2003). Jonghe et al. (2009) studies in a sectoral equilibrium model of the European electricity sector the effects of renewable promotion policies (financed by a price mark-up) on the electricity price. As he assumes a relatively steep renewables supply curve, he finds renewable policies increase consumer prices.[6] Jensen and Skytte (2003) argue in a graphical analysis that renewable promotion policies should be chosen over emission reduction policies when one tries to reach a renewable target when the correlation between the consumer price and the price mark-up induced by the renewable policy is negative.[7] This correlation depends on the market share of renewables and the relative elasticities of fossil and renewable supply, in a way consistent with Fischer (2010).

### 1.2.4 Combining a subsidy for renewables and a cap on emissions

When a subsidy for renewables and a cap on emissions are combined, the previously discussed merit order effect can mitigate the cost pass through effect. Higher renewable subsidies increase the profitability of renewable technologies compared to fossil fuels, and the increased substitution with fossil fuels reduce the overall marginal abatement cost. As a result, the carbon price is reduced, which in turn reduces the consumer electricity price. This effect is labeled *allowance price effect* by Traber and Kemfert (2009), and is described in great detail by numerous studies (see e.g. Harrison et al. (2005) or the review by del Río González (2007)).

### 1.2.5 Combining a subsidy for renewables financed by a tax on electricity consumption and a cap on emissions

Several authors use numerical models to study the interaction effects of renewable subsidies financed by an endogenous tax and a cap on emissions. In a model showing the oligopolistic nature of the European electricity sector, Traber and Kemfert (2009) decompose the interaction between FiTs and the EU-ETS in two competing effects. In the *substitution effect*, increasing the support for renewables induces substitutions from fossil fuel energy toward renewable production. Traber and Kemfert find that this tends to drive the consumer price up. Because fossil supply is relatively rigid compared to renewables, the increased tax necessary to finance the FiT overcomes the merit order effect. Second, in the *allowance price effect*, the reduced stringency of the cap lowers the emission allowance price, which in turns decreases the wholesale and the consumer price.

Traber and Kemfert find that the two effects often almost cancel each other in European member states. The net effect of the interactions between FiT and EU-ETS is however a slight increase in consumer electricity prices in Germany and a slight decrease in other European countries. They also find that the market power of electricity firms tends to mitigate the price decrease.

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6. His model features also emission reduction policies and he studies the interactions between emission reduction and renewable promotion policies, but his analysis on electricity price is limited to renewable promotion policies alone.

7. They study the case of TGC. In their stylized framework, the price of TGC is equal to the price mark-up induced be renewable technologies.

Unger and Ahlgren (2005) develop a numerical model of the electricity sector in the Nordic countries. Their results are in line with the predictions of Fischer (2010). They have an endogenous carbon price, but they assume a relative rigid fossil supply and a relative inelastic demand. They find that a TGC will reduce the consumer price for smaller renewables market shares: for a renewable share of 25 % the consumer price is €3.5/MWh lower than if TGC obligations were absent.

Using a static model of supply and demand of the German electricity sector and an ETS including only this sector, Rathmann (2007) highlights similar effects on the consumer electricity price:

> "On the one hand it is increased through a rising renewables fee, and on the other hand it is decreased through a falling wholesale price due to the effect the additional renewables had on the $CO_2$-price" (Rathmann 2007, p. 345).

In a numerical application to the German electricity sector, he finds a €2.6/MWh decrease in consumer prices due to additional renewables support during the first EU-ETS trading period (2005-2007).

Böhringer and Rosendahl (2010) study the interactions between renewable promotion schemes and an emission cap in a static analytical model of the German electricity sector featuring several technologies with different emission intensities. Their results focus on the impacts of policy interactions on the production level of emitting technologies, but they discuss briefly the variations of consumer electricity prices when the subsidy for renewables vary. They find, in accordance with the results by Fischer (2010), that the effect on the electricity price is in general ambiguous and depends on the comparative elasticities of the electricity supply functions, as well as on the emission intensities. Their results indicate that a price decrease is more likely, as suggests a numerical application in an earlier version of the paper (Böhringer and Rosendahl 2009), but that an increase of the electricity price can occur if emission intensities are very different among producers or if renewable production is very rigid.

## 1.3 MODEL DESCRIPTION

### 1.3.1 Producers and consumers

The model represents a perfectly competitive electricity market featuring a representative producer that maximizes its profit by supplying electricity from two types of energy sources: fossil fuels $(f)$ and renewables $(r)$.

$$\max_{f,r} \Pi = (p - \phi) \cdot f + \rho \cdot r - C_f(f) - C_r(r)$$

$f, r \geqslant 0$ and $p$ is the wholesale price. $\rho$ is the feed-in tariff (FiT) received by renewables producers and $\phi$ is the carbon price (see next subsection). The long term production costs ($C_f$ and $C_r$ respectively) are assumed to be in both cases increasing and convex $(C_f'(f) \geqslant 0$, $C_f''(f) > 0$ and $C_r'(r) >$, $C_r''(r) \geqslant 0$, where $C_i'(i) = \frac{\partial C_i(i)}{\partial i}$ and $C_i''(i) = \frac{\partial^2 C_i(i)}{(\partial i)^2})$. As discussed by Fischer and Preonas (2010), the steepness or flatness of the supply curves depend on the time frame, short term or long term, and on the interactions

**Table 1.1:** Notations used in the models.

| | Dimension | Description |
|---|---|---|
| $f$ | (MWh) | Electricity from fossil fuels |
| $r$ | (MWh) | Electricity from renewables |
| $x$ | (MWh) | Total electricity production |
| $e$ | (MWh) | Savings from energy efficiency |
| $p$ | (€/MWh) | Wholesale power price |
| $\phi$ | (€/MWh) | Carbon tax |
| $\rho$ | (€/MWh) | Feed-in tariff for renewables |
| $\varepsilon$ | (€/MWh) | Energy efficiency subsidy |
| $\Omega$ | (MWh) | Emission cap (in fossil fuel production equivalent) |
| $\alpha_r$ | $(\cdot)$ | Share of renewables in total production |
| $C_f(\cdot)$ | (€) | Cost function of electricity production from fossil fuels |
| $C_r(\cdot)$ | (€) | Cost function of electricity production from renewables |
| $C_e(\cdot)$ | (€) | Cost function of energy efficiency |
| $U(\cdot)$ | (€) | Utility function of consumers |
| $\sigma_f$ | (MWh$^2$/€) | Slope of the supply function for electricity from fossil fuels |

with fossil fuel or land markets.[8] In this chapter, we assume there are decreasing returns to scale for all technologies.

The two goods are assumed perfect substitutes and add up to give the total electricity produced $x$.

$$x = f + r \tag{1.1}$$

Their production is assumed perfectly separable.[9] To give more detail to the welfare analysis, we divide the profit from the representative producer into profit from renewable production and profit from fossil production:

$$\Pi_f = (p - \phi) \cdot f - C_f(f)$$
$$\Pi_r = \rho \cdot r - C_r(r)$$

Consumers maximize a net utility function $\bar{U}$ which is the gross utility $U$ minus the cost of investment in energy efficiency $C_e(e)$ and the cost of electricity purchased:

$$\max_{x,e} \ \bar{U} = U(x + e) - q \cdot x - C_e(e) + \varepsilon \cdot e$$

Consumers purchase electricity at a consumer price $q$, possibly different from the wholesale price $p$ faced by producers. The wedge represents the consumer taxes necessary to finance the subsidy for renewables (see next

8. Cost may differ according to location and the proximity of land markets, yielding different electricity prices. The decreasing returns assumption is justified for renewables as the best production sites are used first (e.g. sites with most sun or wind) and that further development implies investing in less and less productive sites. The cost functions of some fossil fuel technologies such as combined cycles power plants may be less convex, because small power plants are relatively easily scalable.

9. In reality some economies of scale are possible between the two productions, especially if one considers the grid extensions necessary for these capacity extensions to be part of the long term costs.

subsection). The increasing and concave gross utility ($(U'(x) > 0$, $U''(x) \leqslant 0)$ depends on the quantity of energy service provided by the electricity consumed, e.g. heat or light. This service is assumed to be a linear function of the total electricity consumed $x$ and of the energy savings $e$ enabled by investment in energy efficiency $C_e(e)$. [10]

Consumers can reduce their consumption through energy savings $e$, keeping their energy service level constant. We assume energy savings are produced by investment in energy efficiency made at a cost $C_e$ with decreasing returns with respect to the energy savings ($C'_e(e) \geqslant 0$ and $C''_e(e) > 0$). The decreasing returns are justified because (i) doubling the materials used e.g. in refurbishing a building will not halve its energy consumption and (ii) the most profitable investment are made first. These reductions can represent the electricity savings following a switch to efficient lighting bulbs or a switch to an A+ labeled appliance. [11] The energy service provided by the new equipment is the same, and at a constant utilization rate it consumes less electricity.

These reductions do not refer to sufficiency behaviors, where end-users reduce their energy service consumption as a response to price changes or specific education programs. For a detailed discussion on the differences between efficiency and sufficiency, see Alcott (2008) or Herring (2009). A static form of sufficiency is represented in this framework by the decreasing slope of the net demand function. It represents all energy savings behavior components unrelated to technological improvement and which cannot be easily subsidized. It does not refer to a change in the preferences of consumers, nor on dynamic effects possibly affecting the parameters of the demand function.

These maximization programs result in the following first-order conditions (after simplification):

$$C'_f(f) = p - \phi \tag{1.2}$$
$$C'_r(r) = \rho \tag{1.3}$$
$$U'(x + e) = q \tag{1.4}$$
$$C'_e(e) = q + \varepsilon \tag{1.5}$$

Producers and consumers equalize their marginal value to the effective price they face, whether tariff or wholesale price net from the various price instruments.

### 1.3.2 Policy instruments and welfare function

The regulator sets the level of three exogenous policy variables:

- a FiT for renewables $\rho$,
- a subsidy for energy efficiency $\varepsilon$ (as the main instrument for energy savings promotion are in general fiscal incentives),
- a cap on emissions from fossil fuels $\Omega$.

10. Since marginal utility depends only on the electricity consumed, it is therefore effectively equivalent to an inverse demand function.

11. Electricity is the only energy considered here. We do not take into account possible switches to or from other energy sources such as gas heating or electric vehicles. A proper modeling of these switches should include all energy sources. See e.g. the model by Giraudet et al. (2010).

The clearing of the emission allowance market associated with the emission cap yields:

$$f = \Omega \tag{1.6}$$

and results in a carbon price $\phi$. To finance the FiT, the regulator also sets a tax on electricity consumption $t$. This tax is an endogenous variable and results from the financing constraints:

$$r = \alpha_r(r + f) \tag{1.7}$$

$$q = p + t \tag{1.8}$$

$$t = \alpha_r(\rho - p) \tag{1.9}$$

$\alpha_r$ is the share of renewables in the total production mix. The consumer price is the sum of the wholesale price plus the tax set to finance renewable production.[12] The tax is equal to the implicit subsidy to renewables producers $(\rho - p)$ times the ratio of renewable production on total production $\alpha_r$.

The social welfare is defined as the sum of consumer and producer surpluses, minus the damage from emissions $(\delta \cdot f)$:

$$W(\phi, \rho, \varepsilon) = U(x + e) - C_f(f) - C_r(r) - C_e(e) - \delta \cdot f \tag{1.10}$$

## 1.4 ANALYTICAL RESULTS

### 1.4.1 Adding a FIT decreases electricity prices but increases the consumer tax

PROPOSITION 1.1. When a FiT financed by a tax on electricity consumption is combined with an emission cap, increasing the renewables support level results in an increase in the consumption tax and a decrease in the consumer and the wholesale electricity prices. The decrease in the consumer price is bigger as renewable supply is more elastic, energy efficiency supply is less elastic and electricity demand is less elastic; it is however independent from the share of renewables in the production mix.[13]

*Proof.* See Appendix A.1. □

The intuition behind this result is rather straightforward. When an emission cap with an endogenous carbon price is considered, the substitutions between energy sources change compared to the settings considered in the literature reviewed previously. In particular, setting the cap fixes the level of fossil fuel production and hinders the substitutions with renewables. As a result, increasing the support level for renewables increases the total electricity production, and hence leads to a decrease in consumer electricity prices, in what could be labeled an *electricity consumption effect*.

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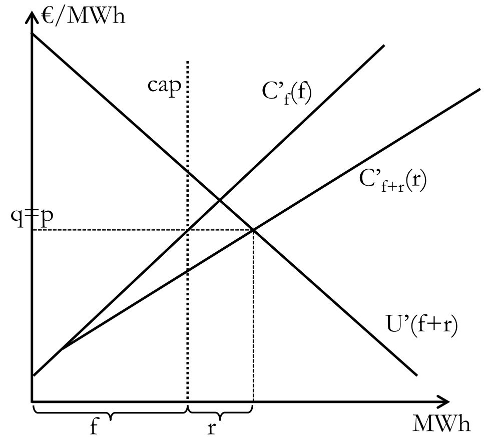
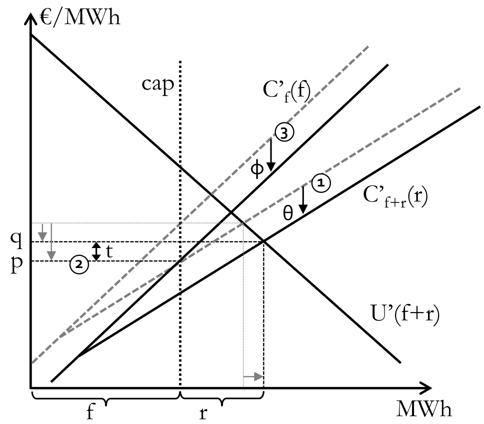
12. We do not take into account transmission costs or other markups that would introduce an additional wedge between the wholesale and consumer prices. Since we focus on price changes and not absolute levels, the analysis is not affected as long as those markup costs are fixed and unaffected by the renewable energy policy. Transmission costs could be non linear, e.g. be small for substantial amounts of solar energy installed on rooftops and mainly used in situ, or on the opposite very high for smaller amounts, e.g. for an off-shore windmill farm. Those effects are however very difficult to quantify.

13. The fossil production is assumed fixed by the emission cap. This is not true if several non-renewable technologies with very different emission rates (e.g. with nuclear production) or the possibility of efficiency investments in the fossil production plants are considered.




**(a)** Market equilibrium with an emission cap alone. The fossil production $f$ is set by the cap. The total electricity production includes renewables and is determined by the intersection between the inverse demand curve $U'(f+r)$ and the inverse total supply curve $C'_{f+r}(r)$. The wholesale price $p$ and the consumer price $q$ are equal.




**(b)** Market equilibrium when adding a subsidy for renewables $\theta$ financed by a tax on consumption $t$. The inverse renewable supply curve is shifted downward (1), and the tax $t$ necessary to finance it creates a wedge between consumer $q$ and wholesale $p$ prices (2). This concurs with a decrease in the inverse fossil supply curve, sharper than the tax increase, caused by a drop in the carbon price $\phi$ (3).

**Figure 1.1:** Adding a subsidy for renewables financed by a tax on consumption to an emission cap.

Figure 1.1 details the mechanisms at play. When there is only a binding emission cap, the level of renewable production is set by the intersection between the demand curve and the total supply curve (see Fig. 1.1a). When adding a net subsidy for renewables, the marginal cost function of renewables is shifted downward, creating a financing need and therefore a wedge between wholesale and consumer prices. This concurs with a decrease in the inverse fossil supply curve, sharper than the tax increase, caused by a drop in the carbon price (see Fig. 1.1b).

The increase due to the consumption tax is dominated by the decrease due to the carbon price. In other terms, the consumer price decrease is only possible by a decrease of the carbon rent possessed by either fossil producer or the regulator (in case of e.g. auctioned allowances). It may be stressed again that this proposition assumes a perfect competition framework and a constant emission rate for fossil production. In an imperfect competition framework, firms may not fully pass through the carbon price decrease;[14] and with a variable emission rate (due to efficiency investments in one technology or to the existence of several non-renewable technologies with different emission rates), non-renewable production cannot be assumed fixed anymore.

### 1.4.2 The FIT and the subsidy for energy efficiency interact through the electricity markets

PROPOSITION 1.2. Adding an subsidy for energy efficiency decreases the consumer and the wholesale electricity prices, and increases the consumption tax. The subsidy for energy efficiency increases savings through efficiency behaviors, but reduces sufficiency behaviors. The FiT on the opposite reduces both sufficiency and efficiency behaviors.

*Proof.* See Appendix A.2. □

The subsidy for energy efficiency and the FiT for renewables have additional effects on the electricity prices and the tax, but do not incentivize the same behavior. While both the FiT and the subsidy for energy efficiency increase the total energy service consumed, thereby reducing sufficiency behaviors, they have diverging effects on efficiency investment. By setting a level of profitability for renewable producers, the FiT is not affected by changes in the subsidy for energy efficiency, but does trigger substitutions from investment in energy efficiency toward renewable electricity production.[15] The increased energy service consumed leads to an intensified *electricity consumption* effect described earlier. This results in a lower consumer and wholesale electricity price, and in a proportionally higher wedge between the two.

14. In an oligopoly framework *à la Cournot*, the cost pass through depends on the utility function form. This would be an interesting avenue for future research.

15. The fact that electricity production is unaffected by investment in energy efficiency is a major assumption, stemming from the simplified choice of technologies made in this model. Having in particular nuclear energy, affected neither by the FiT nor by the emission cap introduces an additional varying parameter. Nuclear plants may close due to the reduced electricity price, as was the case in the USA, thereby mitigating the effect of both the FiT and the subsidy for energy efficiency.

### 1.4.3 Tightening the emission cap has ambiguous effects

PROPOSITION 1.3. Tightening the emission cap increases the consumer electricity price but has an indeterminate effect on the consumption tax, the wholesale electricity price and the carbon price. Tightening the cap is more likely to increase both the consumer electricity price and the carbon price when supply and demand functions are inelastic, the share of renewables in total production and the FiT are small.

*Proof.* See Appendix A.3. □

The ambiguous effect of tightening the cap comes from two countervailing effects:

1. On the one hand, tightening the cap decreases the total electricity production but leaves unchanged the amount of renewables. The tax needed to finance the FiT thus rises proportionally to the level of the FiT and the quantity of renewables, since it applies to smaller quantities of electricity sold.
2. On the other hand, tightening the cap also increases the quantity of efficiency investment because energy savings replace fossil electricity ($\frac{\partial e}{\partial \Omega} < 0$). This tends to mitigate the consumer price decrease, and hence mitigates the decrease in the wedge between consumer and wholesale prices, a smaller tax is enough.

The first effect is stronger when the FiT and the quantity of renewables is high, and the second when demand and energy efficiency supply functions are inelastic.

This explains that a tightening of the cap may have an ambiguous effect on the carbon price. When supply functions are very elastic, marginal costs vary little with quantities. As a result, decreasing the cap only induces a small increase in the resulting marginal abatement cost curve (which depends on all possible substitutions between fossil, renewables, efficiency and sufficiency behaviors). In such situations, it is theoretically possible that the tax increase is bigger than the carbon cost decrease, and to observe a reduction in both the emissions and the carbon price.

This is however difficult to imagine in real life, where the carbon market serves as a signal of the stringency of the climate policy, and where the opposite seems more reasonable: the decrease in the wholesale price follows a decrease of the carbon price.

### 1.4.4 Increasing the FIT generates surplus transfers

PROPOSITION 1.4. Adding a FiT financed through a consumer tax to an emission cap and a subsidy for energy savings:

- decreases the total welfare if the subsidy for energy efficiency is low enough,
- increases the consumer surplus and the profit of electricity production from renewables,
- leaves the profit from fossil production unchanged (if allowances are auctioned),
- decreases the carbon rent.

*Proof.* See Appendix A.4. The signs of the partial derivatives of the various surpluses with respect to the policy variables are gathered in Tab. 1.2. □

**Table 1.2:** Signs of the partial derivatives of the total welfare ($W$), the consumer surplus ($\bar{U}$), the producer profits ($\Pi_f, \Pi_f$) and the carbon rent ($\mathcal{R}_\phi$) with respect to policy variables (emission cap ($\Omega$), FiT for REP ($\rho$) and subsidy for energy efficiency ($\varepsilon$)).

| | $dW$ | $d\Pi_f$ | $d\Pi_r$ | $d\bar{U}$ | $d\mathcal{R}_\phi$ |
|---|---|---|---|---|---|
| $d\Omega$ | $-/+^{(1)}$ | $+$ | $\cdot$ | $+$ | ? |
| $d\rho$ | $-^{(2)}$ | $\cdot$ | $+$ | $+$ | $-$ |
| $d\varepsilon$ | $-$ | $\cdot$ | $\cdot$ | $+$ | $-$ |

*Intersection of line $j$ and column $i$ gives the sign of $\frac{\partial i}{\partial j}$. Table elements are positive ($+$), negative ($-$), nil ($\cdot$) or indeterminate ($?$).*

*(1): when the carbon price is optimal, i.e. if $\phi = \delta$, changing the cap decreases welfare. When the carbon price is below the marginal damage from emissions, tightening the cap increases welfare except when the FiT or the subsidy for energy savings are very large.*

*(2): when the subsidy for energy efficiency is low enough, i.e. if $\varepsilon < (1-\alpha_r)(\rho - p)\frac{\sigma_e - \sigma_u}{\sigma_e}$*

The FiT acts as a transfer from fossil production to renewable production and consumers. If fossil producers pay for their emissions, e.g. when emission allowances are auctioned, increasing the FiT will not affect profits from fossil production. The profit losses induced by the decreasing wholesale price are exactly compensated by the decreasing carbon costs.

Increasing the FiT will however reduce the carbon rent by reducing the carbon price, and transfer a part of this rent to renewables producers and consumers through the decreased consumer price and the increased FiT and renewable production. The total welfare decreases however, except when the subsidy for energy efficiency is so large that the substitutions away from energy savings induced by the FiT reduce the excessive cost of this policy.

Comparably, increasing the energy savings induces transfers from the carbon rent to consumers, with a negative effect on the total welfare because it brings no additional emission reductions compared to the cap and only increases the total compliance costs. Tightening the cap will reduce the profits from fossil production and the consumer surplus. When the cap is such that the carbon price is at its Pigovian level (e.g. equal to the marginal environmental damage from emissions $\delta$, in reference to Pigou (1920)), changing the cap always reduces the welfare. When the price is lower than the marginal damage and the FiT and subsidy for energy efficiency are relatively low, tightening the cap increases the welfare.

Tightening the emission cap has an ambiguous effect on the carbon rent. For smaller values of the cap, reducing the cap has a negative effect on the carbon rent, but for larger values of the cap it has a positive effect. There is one unique intermediate level of the cap for which the carbon rent is maximal. The carbon rent is bell-shaped ad resembles a Laffer curve: increasing the cap has first a positive effect on the carbon rent by increasing the quantity of fossil energy paying a carbon cost, until a maximum level depending on the level of the FiT and the subsidy for energy efficiency, and then decreases again as the carbon price gets negligible (see Appendix A.5 for the calculations).

The effect of the FiT on the cap maximizing the carbon rent is analytically indeterminate, but the negative effect of decreasing the carbon price likely dominates. Assuming a first-best solution, i.e. a FiT equal to the electricity price and a nil efficiency subsidy, the cap maximizing the carbon rent increases as supply and demand curves get more elastic.

## 1.5 DISCUSSION AND CONCLUSION

Using an analytical model of supply and demand of the electricity sector featuring the main climate and policy instruments implemented in European member states, this chapter studies the effects of policy interactions on the electricity price, and the impacts on surplus transfers. I find that when an emission cap is combined with an subsidy for energy efficiency and a tax on electricity consumption to finance a feed-in tariff (FiT) for renewables, increasing the FiT decreases the consumer price, along with the wholesale and the carbon prices. This remains true with a subsidy for energy efficiency, but holds only if the fossil production can be assumed fixed by the emission cap, if one assumes that the fossil electricity production does not vary with the carbon price. This assumption does not hold if several non-renewable technologies with very different emission rates (e.g. with nuclear production) or the possibility of efficiency investments in the fossil production plants are considered.

When fixed by the emission cap, fossil fuel production does not replace renewables, and as the total electricity production increases with the FiT, the electricity market equilibrium shifts toward a lower consumer price. The marginal cost function for renewables is shifted downward by the FiT, creating a financing need and therefore a wedge between wholesale and consumer prices. As this wedge grows, the wholesale price decrease is even sharper than the consumer price, caused by a drop in the carbon price following the loosening of the emission constraint.

Increasing the subsidy for energy efficiency and the emission cap trigger similar interactions using the same channel, in what I label an *electricity consumption* effect. Both instruments lead to an increased energy service consumption, and hence tend to decrease the consumer price. While the efficiency subsidy increases efficiency behaviors and decreases sufficiency behaviors, the FiT reduces both sufficiency and efficiency behaviors, because it causes renewable production to replace some of the efficiency investments at equilibrium.

While all instrument changes reduce the total welfare when the carbon price is at its Pigovian level, adding a FiT or an subsidy for energy efficiency cause transfers from the carbon rent to the consumer surplus. In addition, the FiT increases the renewables producer profit but leaves the profit from fossil production unchanged (when emission allowances are auctioned, i.e. when the carbon rent is owned by the regulator). The carbon rent follows a Laffer curve with respect to the emission cap. There is a cap level maximizing the carbon rent; below, increasing the cap has a positive effect on the carbon rent and above, it has a negative effect on the revenues from the allowance auctions.

This chapter details some of the interactions at play in climate and energy policy mixes widely used in most European member states, and proposes a new mechanism accounting for the effect of an endogenous tax financing the renewable promotion scheme. Relaxing several major simplifying assumptions would be interesting avenues for future research. This chapter assumes that the European Union Emission Trading System (EU-ETS) covers only the emissions from the electricity sector. Having a carbon price depending on external factors would de facto reduce the electricity consumption effect described here. Considering other industrial sectors would however probably only amplify the drop in the carbon price caused by the FiT, as the electricity sector is price maker on the EU-ETS and is the only sector being short in allowances (see Chapter 4).

Another major assumption relates to the production technologies. This chapter only considers two electricity generation technologies, and they are assumed independent. In reality, the long term cost function of fossil technologies can be expected to depend on the level of renewable production, especially for large market shares. As the operating hours of fossil power plants decrease, the time during which the fixed investment costs have to be financed decreases as well, and the share of fixed costs in the total cost function may increase. For larger FiT, this would probably mitigate to some extent the decrease in the marginal cost curve of fossil electricity caused by the drop in the carbon price following a FiT increase.

Considering other types of technologies would also affect the results. As discussed by Böhringer and Rosendahl (2010), if their emission intensities differ, different non-renewable technologies will not respond in the same way in the carbon price decrease, and the non-renewable production may vary even if the emission cap is constant. This may be particularly true when technologies have very different emission intensities, e.g. in a mix with a lot of nuclear and some coal power plants. The price decrease will more affect nuclear plants, whose marginal costs will not decrease if the carbon price drops. This may lead to the closing of some of the nuclear capacity, as was the case in the USA, and lead to non-linear effects on the electricity price.

The assumption of perfect competition may also reveal unrealistic in the electricity sector, where production is very centralized. As discussed by Traber and Kemfert (2009), market power may affect the carbon cost pass through of electricity producer, and mitigate the effect of carbon price decreases on the wholesale price. Lastly, the static and certain framework may also influence the interactions between climate and energy instruments. In this context, combining instruments to a binding emission cap always decreases welfare, and the effects described are all second best phenomenon happening when several instruments are already present for reasons different from carbon emission reductions. Chapter 2 studies the optimal policy choice in a second-best framework where uncertainty on the demand for electricity results in a risk that the EU-ETS carbon price drops to zero. Chapter 3 studies a dynamic model of the electricity sector, examining the role of capital accumulation and congestion effects in investment in the optimal transition toward a carbon free electricity sector.

Finally, we assume the instruments apply all at to the whole electricity market, i.e. at the European level. This is not true for renewable FiT. In fact, FiT may have effects across borders. For instance, as the German coal plants often set the spot price of the French-German-Belgium electricity market in winter, increasing the German FiT tariff would decrease the spot price for the whole market, but the corresponding tax would only increase in Germany.

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# 2 CAN UNCERTAINTY JUSTIFY OVERLAPPING POLICY INSTRUMENTS TO MITIGATE EMISSIONS? [1]

## 2.1 INTRODUCTION

All countries and regions having implemented climate policies seem to rely on several policy instruments, some of which covering the same emission sources, rather than a single one [2]. In the European Union, $CO_2$ emissions from the electricity sector are directly or indirectly covered by the European Union Emission Trading System (EU-ETS) (Ellerman et al. 2010), by energy-efficiency standards and energy-efficiency labels on electric motors and appliances (EU 2009), by $CO_2$ or energy taxes (in some Member States), by energy-efficiency obligations [3] (in some Member States), and by renewable energy power (REP) subsidies, in the form of feed-in tariffs, feed-in premiums or Renewable Portfolio Standard (RPS) obligations (in virtually all Member States).

This multiplicity of policy instruments is in sharp contrast to the so-called Tinbergen rule (Tinbergen 1952) requiring in order to achieve a given number of targets that policymakers control an equal number of instruments. Unsurprisingly, this multiplicity has generated criticism by some economists who argue that the policy instruments complementing the EU-ETS do not reduce $CO_2$ emissions (which are capped) but reduce the allowance price on the EU-ETS market and generate costly economic distortions (Cf. for instance Böhringer and Keller (2011), Braathen (2007), Fischer and Preonas (2010) or Tol (2010)). Indeed, some abatement options, such as REP sources, are covered by several instruments and benefit from a higher implicit carbon price than others, such as coal-to-gas switch. The mix of instruments promoting the same abatement options is therefore suboptimal, at least in a simple economic model, as it disregards the equimarginal principle and leads to sometime antagonist interactions (Lecuyer and Bibas 2011).

Yet, the multiplicity of policy instruments has been justified by some other economists, on several grounds. First, and most obviously, other policy targets such as air pollution reduction and security of supply are differently impacted by the various $CO_2$ abatement options. Second, induced technical change may be higher for some options than for others. For instance, the deployment of photovoltaic panels is likely to induce more technical change than coal-to-gas switch (see Fischer and Newell (2008) for a review). Third, the slow diffusion of clean technology justifies implementing more costly but higher potential options, such as photovoltaic panels, before the cheaper but lower potential options, such as coal-to-gas switch (Vogt-Schilb and Hal-

1. This chapter has been coauthored with Philippe Quirion, supervisor of this thesis. It has been published as Lecuyer and Quirion (2013). Elements of discussion not part of the published version can be found in a complement on page 123 of this document.
2. The unconvinced reader is invited to look at the National Communications to the UNFCCC: http://unfccc.int/national_reports/items/1408.php
3. Lees (2012) provides a recent survey of these systems in Europe, while Giraudet et al. (2012) discuss the costs and benefits of these systems.

legatte 2011). Fourth, some market failures, regulatory failures or behavioral failures may reduce the economic efficiency of market-based instruments and justify additional policy instruments (Gillingham and Sweeney 2010). For instance, the landlord-tenant dilemma reduces the efficiency of $CO_2$ pricing and can justify energy-efficiency standards in rented dwellings (de T'Serclaes and Jollands 2007), while regulatory failures may lead to a too low carbon price, or prevent governments to commit to a high enough future carbon price (Hoel 2012).

Our aim is not to discuss these justifications, but to introduce and discuss another rationale: the impact of uncertainty on abatement costs combined with the unavailability of the first-best instrument. It is well known since Weitzman (1974) that under uncertainty, the relative slope of the marginal abatement cost curve (MACC) and marginal damage of emissions curve (labeled "marginal benefits" in Weitzman's framework) is key to choose between a price instrument (e.g. a $CO_2$ tax) and a quantity instrument (e.g. a cap-and-trade system, like the EU-ETS). More specifically, in the simplest form of Weitzman's (1974) model, the quantity instrument should be chosen if the marginal damage curve is steeper than the MACC while the price instrument should be chosen if the MACC is steeper. If the marginal damage curve is completely flat then a tax (set at the expected marginal damage) is the first-best instrument. In the case of climate change control, most researchers have concluded that on this ground, a tax should be preferred to a cap-and-trade system (e.g. Pizer (1999)). Indeed the marginal damage curve of $CO_2$ emissions over a few years period is relatively flat because $CO_2$ is a stock pollutant (Newell and Pizer 2003). Actually, this argument is even stronger for policies covering only a small part of total emissions, such as the EU-ETS; hence, with an uncertain MACC, an EU-ETS is less efficient than a tax, i.e. it brings a lower expected welfare.

Yet, in the European Union (EU), a meaningful $CO_2$ tax is out of reach because fiscal decisions are made under the unanimity rule, while a cap-and-trade system has been adopted thanks to the qualified majority rule which applies to environmental matters (Convery 2009). Another main reason why cap-and-trade was chosen was for political economy reason in order to be able to alleviate opposition of e.g. electricity producers by means of free allocation of emission permits [4] (Boemare and Quirion 2002).

The fact that the EU-ETS is not optimal is illustrated by its history since its introduction in 2005, which shows how volatile the carbon price can be: it dropped to virtually zero in 2007 because allowance allocation in phase 1 was too generous (Ellerman and Buchner 2008), recovered up to more than €30/t$CO_2$ because allocation in phase 2 was tighter and dropped again sharply in 2009 following the economic crisis, down to €3/t $CO_2$ in April 2013. While economists disagree over the marginal damage of $CO_2$ emissions, commonly called the "social cost of carbon" (Perrissin Fabert et al. 2012), they would presumably agree that such a price evolution is inefficient: in some periods, the carbon price has prompted relatively expensive abatement options (up to €30/t $CO_2$) while in other periods, cheaper abatement options have not been implemented. This potentially provides a rationale for correcting the EU-ETS and/or for complementing it. Among the proposed corrections is the introduction of a price cap and a price floor. Since this pro-

4. The EU-ETS was also implemented as part of a long-term strategy aiming at setting clear targets for investors. As a market instrument, it also brings value as a coordination tool for investment efforts across a large range of sectors or parts of sectors.

posal has been widely debated (e.g. Hourcade and Ghersi (2002)), we will not address it in this paper.

Conversely, to our knowledge only two papers have addressed the role of uncertainty on abatement costs on the effectiveness of multiple instruments. Mandell (2008) find that under some conditions, it is more efficient to regulate a part of emissions by a cap-and-trade program and the rest by an emission tax, than to use a single instrument. Admittedly, under such a mixed regulation, the marginal abatement cost (MAC) differs across emission sources, which is inefficient, but the emission volume is generally closer to the ex post optimum than under a single instrument: following an increase in the MAC, the tax yields too high an emission level while the cap-and-trade system yields a level which is too low, so these inefficiencies partly cancel out.

The other paper is by Hoel (2012, section 9) who studies the opportunity to subsidize REP in case of an uncertain future carbon tax. He studies the case of scientific uncertainty (damages caused by climate change are uncertain) and political uncertainty (the current government knows that there might be a different government in the future, and that this government may have a different valuation of emissions). He shows that scientific uncertainty justifies a subsidy to REP if REP producers are risk-averse. Under political uncertainty, results are more complex. If the current government expects the future government to have a lower valuation of emission reductions than itself, this tends to make the optimal subsidy positive. Hoel (2012) studies the impact of uncertainty, but only when the subsidy is combined with a tax, not when it is combined with an EU-ETS — which is what the present article focuses on.

While we also address the role of uncertainty concerning abatement costs on the effectiveness of multiple instruments, our focus is on whether it makes sense to use several instruments to cover the same emission sources and not to cover different sources, as in Mandell's article (Mandell 2008). More precisely, we assume that the EU cannot implement a $CO_2$ tax because of the above-mentioned unanimity rule but can implement an EU-ETS. However some $CO_2$ abatement options (for illustration, REP) can be incentivised by a price instrument (in this case, a subsidy to REP, e.g. a feed-in tariff). In our model, without uncertainty on the energy demand level (and hence on abatement costs) or if uncertainty is low enough, using the REP subsidy in addition to the EU-ETS is not cost-efficient because there is no reason to give a higher subsidy to REP than to other abatement options. However we find that this uncertainty provides a rationale for using the REP subsidy in addition to the EU-ETS, if it is large enough to entail a risk of a nil carbon price[5]. Even though the first-best policy would be a $CO_2$ tax, when the latter is unavailable, using both a REP subsidy and an EU-ETS may provide a higher expected welfare than using an EU-ETS alone.

We demonstrate this result using three approaches. Section 2.2 presents the intuition in a graphical way. Section 2.3 develops an analytical model and presents some key analytical results based on the same intuition. Section 2.4 further completes the model and presents a numerical application on the European electricity sector. Section 2.5 concludes.

5. Since we use an expected welfare maximization model with a subjective probability distribution, we do not distinguish between risk and uncertainty.

## 2.2 THE POSSIBILITY OF A NIL CARBON PRICE: IMPLICATIONS FOR INSTRUMENT CHOICE

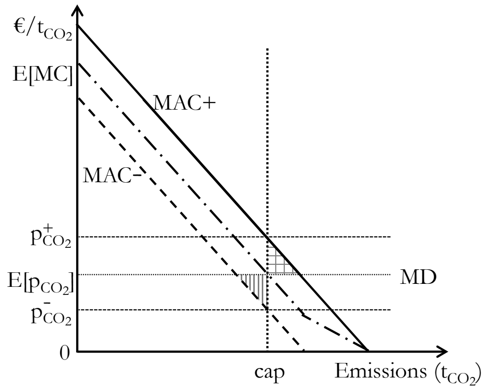
This section presents our main conclusion in an intuitive and graphical way. We study the possibility of a nil carbon price, unaccounted in Weitzman's seminal Prices vs. Quantities paper (Weitzman 1974) or in the related literature, on optimal policy instrument choice. We show that using a REP subsidy in addition to the EU-ETS improves expected welfare in so far as uncertainty on the demand level is large enough to entail a possibility of a nil carbon price, i.e. if there is a possibility that demand for greenhouse gases (GHG) quotas turns out to be so low, compared to its expected value, that the EU-ETS cap becomes non-binding.

Before introducing the intuition, let us give some elements justifying the possibility of a nil carbon price, in the light of the experience with cap-and-trade systems. An allowance price dropping to zero in an EU-ETS is not unrealistic at all, and happened in some of the most well-known EU-ETS worldwide. In the EU-ETS, the carbon price dropped to zero at the end of the first period (in 2007). It would have done so in the second period (2008-2012) again without the possibility to bank allowances for the next period (2013-2020) and the likelihood of a political intervention to sustain the price. In the Regional Greenhouse Gases Initiative (RGGI), which covers power plant $CO_2$ emissions from North-Eastern US states, phase one carbon emissions fell 33% below cap (Point carbon 2012). Consequently, the price remained at the auction reserve price, below \$2/t$CO_2$. The cap also turned out to be higher than emissions in the tradable permit program to control air pollution in Santiago, Chile (Coria and Sterner 2010) and in the UK greenhouse gas EU-ETS (Smith and Swierzbinski 2007). Even in the US $SO_2$ EU-ETS, the price is now below \$1/t$SO_2$ (Schmalensee and Stavins 2012), vs. more than \$150/t$SO_2$ ten years before, because new regulations and the decrease in high-sulfur fuels consumption have reduced emissions below the cap.

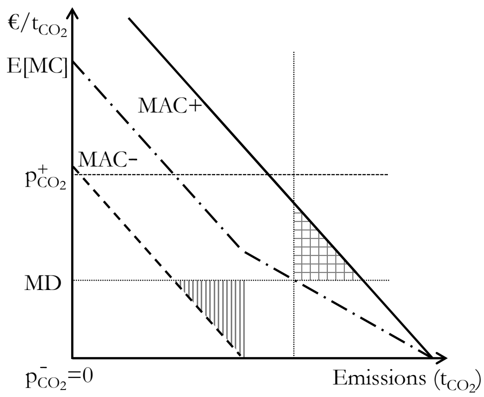
Figure 2.1 present grpahically the implications of the possibility of a nil carbon price on optimal policy instrument choice. For our purpose, it is more convenient to draw the marginal cost and marginal damage as a function of emissions rather than as a function of abatement (as in Weitzman's paper), because we are interested in the uncertainty of unabated emissions. Let's assume that the Marginal Damage *MD* is known with certainty and is perfectly flat. We do not model the uncertainty on the marginal damage side since it is well known that this uncertainty matters only when correlated with abatement cost (Stavins 1996, Weitzman 1974). In our model, as in these two papers, adding (uncorrelated) uncertainty on marginal damages from emissions would not influence the ranking of instruments. Let's further assume than the MACC is uncertain and can take with an equal probability two values, *MAC+* and *MAC-* [6], representing for instance the two extreme cases of a probability distribution. This uncertainty on the MACs captures economic uncertainty, as well as uncertainty on the technological costs (Quirion 2005). In Figure 2.1a, uncertainty is lower (*MAC-* (decreasing dashed line) and *MAC+*(decreasing solid line) are closer) than in Figure 2.1b and 2.1c.

Since the marginal damage of emissions *MD* is known with certainty and perfectly flat, a price instrument (like a $CO_2$ tax) is optimal, both *ex-ante* and *ex-post*. On the opposite, a quantity instrument (like an emission cap or

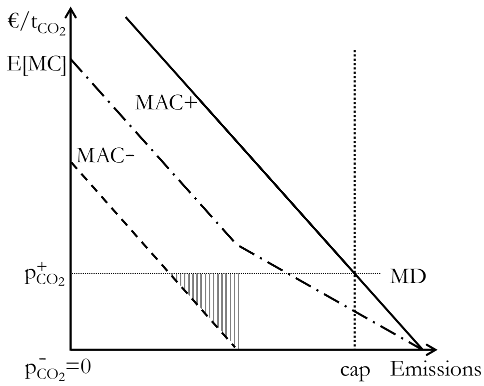
6. Noted MC in Weitzman (1974).




**(a)** Instrument choice with low uncertainty: the policy-maker sets the cap at the intersection of the expected marginal costs and the marginal damage of emissions, minimizing the expected extra cost compared to the *ex-post* optimum (area with vertical lines in the *MAC-* state and area with squares in the *MAC+* state).




**(b)** Instrument choice with high uncertainty: here setting a cap at the intersection of the expected marginal costs and the marginal damage of emissions does not minimize the total costs. The carbon price is nil in the *MAC-* state.




**(c)** Instrument choice with high uncertainty: setting the cap at the intersection of the *MAC+* marginal costs and the marginal damage of emissions minimizes the costs in the *MAC+* state with no additional costs in the *MAC-* state.

**Figure 2.1:** The implications of the possibility of a nil carbon price on optimal policy instrument choice.

the EU-ETS) is generally not optimal *ex-post* because the cap does not follow the (*ex-post*) optimal emission level. Let's analyze how a risk-neutral policy maker minimizing expected cost (or maximizing expected welfare) would set the cap.

In Figure 2.1a, with a low uncertainty, the policy maker would set the optimal cap at the intersection between the marginal damage of emissions and the expected MACC (the dotted-dashed line). This is also the expected emission level under a price instrument. The expected carbon price would then equal the marginal damage of emissions[7] , although ex post, the carbon price would be either higher ($p^+_{CO_2}$) or lower ($p^-_{CO_2}$) than the expected carbon price ($E[p_{CO_2}]$). The cost of the quantity instrument compared to the price instrument (or to the optimum) is given by the area with squares (in case of a higher than expected cost) or by the area with vertical lines (in case of a lower than expected cost). All this is consistent with Weitzman's standard model.

Conversely, in Figure 2.1b which features a large uncertainty, setting the optimal cap at the intersection between the marginal damage and the expected MACC (vertical dotted line) does not minimize the expected cost: such a cap would not be binding in the *MAC-* state, but it would entail a significant cost, both in the *MAC-* state (the area with vertical lines) and in the *MAC+* state (the area with squares).

A better solution (Figure 2.1c) is to set a more lenient cap which equalizes the MAC and marginal damages of emissions only in the *MAC+* state: the extra cost compared to the price instrument would then be nil in the *MAC+* state while it would still equal the area with vertical lines in the *MAC-* state. In other words, the policymaker now neglects the *MAC-* state, knowing that in such an eventuality, the cap is non-binding anyway; rather he sets the cap which is optimal is the high-cost state.

Notice in Figure 2.1c that in the *MAC+* state, the MAC equals the marginal damage; hence the welfare loss from a marginal additional effort would only be of the second order. Conversely, in the low-cost state, the MAC is below the marginal damage; hence the welfare gain from a marginal additional effort would be of the first order. Consequently, an additional policy instrument might improve welfare even if it entails additional abatement in both states of nature, and even if it is imperfect — for example, because it targets only a subset of abatement options, like a REP subsidy.

Having explained the intuition of our main results, we now turn to the presentation of the analytical model.

## 2.3 KEY ANALYTICAL RESULTS IN A STYLIZED ELECTRICITY MARKET

To discuss the implications of a possible nil carbon price on the electricity sector, we model in this section a stylized European electricity market with an uncertain demand. This uncertainty on the electricity demand results in

7. This equality (in expectation) between the price instrument and the quantity instrument regarding price and quantity is dubbed "certainty equivalence" by Hoel and Karp (2001). They find that while the equivalence prevails with additive uncertainty (a shift of the MACC as in Weitzman's original paper), it does not under multiplicative uncertainty (a change in the slope of the MACC). In this paper, we find that even with additive uncertainty on abatement costs, this principle does not prevail if there is a possibility that the price drops to zero.

an uncertain abatement effort for any given emission cap, and hence in an uncertain marginal abatement cost (MAC), as in the previous section.

We first present the equations and the programs of the producers and the social planner. The setting presented here corresponds to a mix with an European Union Emission Trading System (EU-ETS) and a renewable energy power (REP) subsidy. Appendix B.3 and following present the other settings used in our analytical results.

### 2.3.1 Analytical framework and equations

We represent three types of agents: a social planner, representative electricity producers and representative consumers. The social planner maximizes an expected welfare function by choosing the optimal level of various instruments depending on the available instrument set: a carbon tax, an emission cap for the electricity sector or a REP subsidy. For demonstration purposes we focus in the model presentation on a setting with an emission cap and a REP subsidy.

The emission cap can be interpreted as a stylized representation of the EU-ETS. The future level of electricity demand is uncertain, with a risk that the carbon price drops to zero in case of low demand. The electricity market is assumed to be perfectly competitive and we assume a 100% pass-through of the emission allowance.

The model is a two-stage framework. In the first stage, the social planner chooses the level of the various policy instruments, facing an uncertainty about the level of future electricity demand. In the second stage, the electricity producers maximize their profit given the policy instrument levels and the demand function.

#### 2.3.1.1 *Step 1: the producer profit maximization problem*

We consider two types of electricity generation: fossil fuels $(f)$ and REP $(r)$. The electricity producers can also make abatement investments $(a)$ to comply with the emission cap. Those abatements are assumed for simplicity to be independent from the level of fossil-based production. They refer for instance to investments making coal-fueled power plants able to cope with some share of biomass, CCS investments or allowance purchases on the Clean Development Mechanism (CDM) market. $p$ is the electricity wholesale price.

Producers face an aggregate emission cap $\Omega$ and benefit from a REP subsidy $\rho$. $\phi$ is the carbon price emerging from the allowance market, equal to the shadow value of the emission cap constraint. We assume a 100% pass-through from allowance costs to wholesale price. In our framework, $\rho$ can be seen as a feed-in premium for instance. The producer maximizes its profit $\Pi$ (Table 2.1 describes all the variables and parameters).

$$\begin{aligned}\max_{f,r,a} \Pi(p, f, r, a, \phi, \rho) = {} & p \cdot f + (p + \rho) \cdot r \\ & - C_f(f) - C_r(r) \\ & - AC(a) - PC(f, a, \phi)\end{aligned} \tag{2.1}$$

where $C_f(f)$ and $C_r(r)$ are the production costs from fossil fuel and REP respectively. We assume decreasing returns for REP and constant returns for emitting power plants $(C_f'(f) > 0, C_r'(r) > 0, C_f''(f) = 0$ and $C_r''(r) > 0)$. The decreasing returns assumption is justified as the best production sites are used first and further REP development implies investing in less and less productive sites. On the contrary, emitting technologies such as combined cycles power plants or advanced coal power plants are easily scalable and thus do not generate a scarcity rent (Fischer 2010, Fischer and Preonas 2010, Jonghe et al. 2009). $AC(a)$ is the Abatement Cost function of the electricity producers, independent of fossil or REP production and $PC(f, a, \phi)$ is the allowance Purchasing Cost. The cost functions have a classical linear-quadratic form:

$$\begin{aligned}
C_f(f) &= \iota_f \cdot f \\
C_r(r) &= \iota_r \cdot r + \frac{r^2}{2\sigma_r} \\
AC(a) &= \frac{\sigma_a}{2} a^2 \\
PC(f, a, \phi) &= \phi \cdot (\tau \cdot f - a)
\end{aligned}$$

With $\iota_f$ and $\iota_r$ the intercepts (iota like intercept) of the fossil fuel and the REP marginal supply function respectively and $\sigma_r$ the slope (sigma like slope) of the REP marginal supply function[8]. $\sigma_a$ is the slope of the marginal abatement cost curve (MACC) for the electricity producer and $\tau$ is the average unabated carbon intensity of fossil fuel-based electricity production. We define a linear downward sloping electricity demand function $d(\cdot)$ (with $d'(\cdot) < 0$) whose intercept depends on the state of the world. We consider two different states $s$ occuring with a probability $\mathcal{P}_s$, one with a high demand ($d_+(p)$) and one with a low demand ($d_-(p)$). The demand function is defined as:

$$d(p) = \iota_d \pm \Delta - \sigma_d \cdot p$$

with the intercept being $\iota_d + \Delta$ in the high-demand state of the world and $\iota_d - \Delta$ in the low-demand state. The equilibrium conditions on the electricity and the emission markets thus depend on the state of the world.

$$f + r = d(p) \tag{2.2}$$

is the demand constraint. In each state of the world, the electricity supply has to meet the demand on the electricity market.

$$\begin{cases} \tau \cdot f_- - a_- < \Omega \\ \phi_- = 0 \end{cases} \quad \text{or} \quad \begin{cases} \tau \cdot f_+ - a_+ = \Omega \\ \phi_+ > 0 \end{cases} \tag{2.3}$$

expresses the joint constraint on emissions and carbon price. In the high-demand state of the world, total emissions cannot be higher than the cap $\Omega$ and the carbon price is therefore strictly positive. In the low-demand state, we assume that the emission cap constraint is non-binding, hence the carbon price is nil.

The first order conditions of the producer maximization problem are the following:

$$p = \iota_f + \tau\phi \tag{2.4}$$

8. The supply functions are the expression of the quantity produced as a function of price. This corresponds to the inverse of the marginal cost function, and the slope of the supply function ($\sigma_r$) is the inverse of the slope of the marginal cost function ($\frac{1}{\sigma_r}$). We constructed the REP cost function this way in order to keep the dimension of $\sigma_r$ consistent with the slope of the demand function $\sigma_d$, allowing for some simplifications in the equations.

**Table 2.1:** Notations used in the models.

| | Dimension | Description |
|---|---|---|
| $f$ | (MWh) | Electricity from fossil fuels |
| $r$ | (MWh) | Electricity from REP sources |
| $p$ | (€/MWh) | Wholesale power price |
| $a$ | ($tCO_2$) | Abatements from power sector |
| $\phi$ | (€/$tCO_2$) | Carbon price |
| $\rho$ | (€/MWh) | REP subsidy |
| $\Omega$ | ($tCO_2$) | Emission cap |
| $\sigma_a$ | (€/ ${tCO_2}^2$) | Slope of power sector MACC |
| $\sigma_d$ | ($MWh^2$/€) | Slope of demand function |
| $\sigma_r$ | ($MWh^2$/€) | Slope of RE supply function |
| $\delta$ | (€/ $tCO_2$) | Marginal environmental damage |
| $\lambda$ | - | Probability of the high-demand state |
| $\Delta$ | (MWh) | Variance of demand |
| $\tau$ | ($tCO_2$/MWh) | Average carbon intensity (fossil fuels) |
| $\iota_f$ | (€/ MWh) | Intercept of fossil fuel supply function |
| $\iota_r$ | (€/ MWh) | Intercept of RE supply function |
| $\iota_d$ | (€/ MWh) | Intercept of demand function |

Fossil fuel producers will equalize marginal production costs with the wholesale market price, net from the price of emissions.

$$\rho + p = \iota_r + \frac{r}{\sigma_r} \tag{2.5}$$

REP producers will equalize marginal production costs with the wholesale market price, net from the subsidy.

$$\sigma_a a = \phi \tag{2.6}$$

Fossil fuel producers will equalize the MAC with the carbon price.

The values of the market variables $(p, f, r, a, \phi)$ as a function of policy instruments are found by solving the system of equations (2.2) to (2.6). They represent the reaction functions of the electricity producer.

#### 2.3.1.2 *Step 2: the social planner's expected welfare maximization problem*

The social planner, assumed risk-neutral and giving the same weight to consumers and producers, faces an uncertain future demand and has a limited number of possible policy instruments (i.e. an emission cap and a REP subsidy) to maximize the expected welfare. We assume no social externality on the public funding, as this would imply that all public goods become more expensive, including the environment. We would have to add a deadweight loss on the revenues from the emission cap allowances transfers, and distinguish several cases with and without auction. We keep therefore our welfare function as simple as possible:

$$\begin{aligned}\max_{\Omega,\rho} EW(\Omega, \rho) = \sum_{s \in \text{states}} & \mathcal{P}_s(CS(p) \\ & + \Pi(p, f, r, a, \phi) - dam(f, a) \\ & - \rho \cdot r + PC(f, a, \phi))\end{aligned} \tag{2.7}$$

$\mathcal{P}_s$ is the probability of the two states of the world: $\mathcal{P}_+ = \lambda$ and $\mathcal{P}_- = (1 - \lambda)$, $\lambda \in [0, 1]$. $CS(p)$ is the consumer surplus and $dam(f, a)$ is the environmental damage function from the greenhouse gases (GHG) emissions. The last two terms of the expected welfare cancel pure transfers between agents included in the profit functions. The consumer surplus $CS$ and the damage function are taken as simple as possible for clarity. In particular, consumer are assumed risk-neutral:

$$\begin{aligned}CS(p) =& \int_0^{d(p)} d^{-1}(q) dq - p \cdot d(p) \\ dam(f, a) =& \delta \cdot (\tau f - a)\end{aligned}$$

With $\delta$ the constant environmental damage coefficient (Newell and Pizer 2003). After having substituted the market variables in the expected welfare function (2.7) with the reaction functions coming from the producer problem we maximize the expected welfare. The first-order conditions give the optimal levels of the policy instruments across all states ($\rho^\star$ and $\Omega^\star$).

### 2.3.2 Social optimum when the carbon price is nil in the low-demand state

**PROPOSITION 2.1.** When the carbon price is nil in the low-demand state of the world, the optimal REP subsidy is strictly positive.

*Proof.* The optimal levels of the policy instruments across all states are given by solving the first-order conditions of the welfare maximization problem (2.7) (see Appendix B.5).

$$\begin{aligned}\Omega^\star =& \tau\Delta + \tau\iota_d + \tau\iota_r\sigma_r \\ & - \tau(\sigma_d + \sigma_r)(\iota_f + \delta\tau) - \frac{\delta}{\sigma_a}\end{aligned} \tag{2.8}$$

$$\rho^\star = (1 - \lambda)\delta\tau \frac{1 + \sigma_a\sigma_d\tau^2}{1 + \sigma_a(\sigma_d + \sigma_r - \lambda\sigma_r)\tau^2} \tag{2.9}$$

knowing that all parameters are positive, and using the reaction functions from the profit maximization problem (2.1), we can write:

$$0 < \rho^\star < \delta\,\tau \tag{2.10}$$

Results follow directly. □

If we considered only one certain state, we would fall back on the first-best optimum characterized by a REP subsidy equal to zero and the emission cap set so as to equalize the carbon price with the marginal damage $\delta$. The cap is set to be optimal in the high-demand state only, and does not depend on the probability distribution. We see here in (2.10) that the optimal subsidy is a portion of the marginal environmental damage (see also (2.12) below), and is weighted by the probability of the low-demand-state $(1 - \lambda)$.

By substituting the optimal levels of policy instruments in the reaction functions, we obtain the socially optimal level of all market variables for both states of demand (see Appendix B.5).

While in a first-best world the carbon price would equal the marginal environmental damage, in this second-best setting, the optimal carbon price in the high-demand state is lower because the REP subsidy also reduces emissions. The expected carbon price $\mathcal{E}_\phi = \sum_{s \in \text{states}} \mathcal{P}_s \cdot \phi_s$ can be rearranged into:

$$\sum_{s \in \text{states}} \mathcal{P}_s \cdot \phi_s = \delta \cdot \frac{\lambda(1 + \sigma_a \sigma_d (\tau)^2)}{1 + \sigma_a(\sigma_d + \sigma_r - \lambda\sigma_r)\tau^2} \tag{2.11}$$

The term in the denominator expresses the substitutions taking place when the abatement through carbon pricing only is no longer optimal.

PROPOSITION 2.2. When the carbon price is nil in the low-demand state of the world, the REP subsidy equivalent in €/t$CO_2$ is equal to the marginal damage of emissions minus the expected carbon price.

*Proof.* Combining (2.9) and (2.11) gives:

$$\frac{\rho^\star}{\tau} = \delta - \mathcal{E}_\phi \tag{2.12}$$

The proof follows directly. □

In (2.12), $\frac{\rho^\star}{\tau}$ is the marginal abatement effort through REP promotion and $\mathcal{E}_\phi$ is the expected marginal abatement effort through carbon pricing. The simple intuition behind this result is that since the expected carbon price is below the marginal damages, the additional instrument, e.g. the REP subsidy, is also used to reduce emissions.

Since the carbon price is nil in the low-demand state, the expected carbon price decreases with the probability of the high-demand state (everything else being equal). Equation (2.12) reveals that the optimal subsidy moves accordingly to keep the global expected mitigation effort constant and equal to the marginal damage.

### 2.3.3 Expected emissions with various instrument mixes

As mentioned in section 2.2, in Weitzman's model (Weitzman 1974) with an additive uncertainty on the MACC, the expected emissions are the same with a price or a quantity instrument. This is no longer the case in our model.

PROPOSITION 2.3. If there is a risk that the carbon price equals zero in the low-demand state of the world, expected emissions vary with the instrument mix.

*Proof.* See Appendix B.1. □

The expected emissions are lower in the second-best setting (with an EU-ETS and a REP subsidy) than in the third (with an EU-ETS alone) and even lower with a first-best carbon tax.

The expected carbon price changes also. It is lowest in the second-best setting when it is optimal to implement a REP subsidy along with the emission cap.

The drop between first-best and second-best is mostly due to the nil carbon price in the low-demand state of the world. When comparing third-best and second-best, the carbon price is lower because another instrument, the REP subsidy, is now also used to reduce emissions.

**Table 2.2:** Signs of partial derivatives of the difference between the cap minus the emissions in the low-demand state for a nil carbon price.

| Par. | Meaning of an increase in the parameter | Sign of partial derivative |
|---|---|---|
| $\sigma_a$ | Higher abatement cost | + |
| $\sigma_d$ | More elastic power demand | – |
| $\sigma_r$ | Cheaper REP | – |
| $\delta$ | Higher marginal damage | – |
| $\Delta$ | Higher demand variance | + |
| $\lambda$ | Higher probability of the high-demand state | – |

*Elements can be negative (–), positive (+) or indeterminate (?).*

### 2.3.4 Boundary condition for having a nil carbon price in the low-demand state of the world

As discussed in the graphical anlaysis in Section 2.2, the carbon price drops to zero when the optimal cap no longer crosses the low-demand MAC curve. In this section we investigate the effect of a change in the main parameters on the boundary between the positive-carbon price and the nil-carbon price spaces.

PROPOSITION 2.4. On the boundary, the carbon price in the low-demand state drops to zero as mitigation options (abatements and REP) become more expensive, uncertainty on the level of the electricity demand grows, the demand gets more inelastic, the environmental damage gets lower and the low-demand state gets more probable.

*Proof.* We compute the equilibrium conditions of the model without making any assumption about the emission or the carbon price levels in the low-demand state (see Appendix B.2). The expression for emissions, being a decreasing function of the carbon price, give the expression of the MAC curve in the low-demand state.

The difference between the emission cap and the low-demand state MAC curve for $\phi_- = 0$ give then a test of the positivity of the carbon price in the low-demand state. When emissions at $\phi_- = 0$ are below the cap, the carbon price is nil, and when emissions are above the cap, the carbon price is positive.

Table 2.2 gives the sign of the partial derivative of the difference between the cap minus the emissions in the low-demand state for a nil carbon price. On the boundary, if this difference increases, the carbon price drops to zero; if it decrases, the carbon price rises above zero. □

### 2.3.5 Variables' elasticity with respect to parameters

As a preliminary step to the numerical sensitivity analysis presented in Section 2.4, Table 2.3 and Table 2.4 show the sign of the elasticity of all variables with respect to various parameters in the 2nd Best setting (instrument mix $M_2$, see Appendix B.3), and indicate whether they are above or below 1.

**Table 2.3:** Market variables' elasticity with respect to various parameters.

| Par. | Meaning of an increase in the parameter | Level of demand (state) | f<br>fossil fuel | r<br>REP | p<br>elec. price | a<br>abate-ments | $\phi$<br>$CO_2$ price |
|---|---|---|---|---|---|---|---|
| $\sigma_a$ | Higher abatement cost | High (+) | + | – | $]-1;0[$ | $<-1$ | $]-1;0[$ |
| | | Low(–) | – | + | 0 | 0 | 0 |
| $\sigma_d$ | More elastic power demand | High (+) | ? | + | $]0;1[$ | $]0;1[$ | $]0;1[$ |
| | | Low(–) | ? | – | 0 | 0 | 0 |
| $\sigma_r$ | Cheaper REP | High (+) | ? | ? | $]-1;0[$ | $]-1;0[$ | $]-1;0[$ |
| | | Low(–) | ? | ? | 0 | 0 | 0 |
| $\delta$ | Higher marginal damage | High (+) | – | + | $]0;1[$ | 1 | 1 |
| | | Low(–) | – | + | 0 | 0 | 0 |

*Elasticities are between 0 and -1: ]-1;0[, between 0 and 1: ]0;1[, negative (–), positive (+) or indeterminate (?).*

**Table 2.4:** Elasticity of instrument variables with respect to various parameters.

| Par. | Meaning of an increase in the parameter | $\rho$: REP subsidy | $\Omega$: Emission cap |
|---|---|---|---|
| $\sigma_a$ | Higher abatement cost | ]0;1[ | + |
| $\sigma_d$ | More elastic power demand | ]-1;0[ | – |
| $\sigma_r$ | Cheaper REP | ]0;1[ | ? |
| $\delta$ | Higher marginal damage | 1 | – |

*Elasticities are between 0 and -1: ]-1;0[, between 0 and 1: ]0;1[, negative (–), positive (+) or indeterminate (?).*

PROPOSITION 2.5. the optimal subsidy $\rho^\star$ rises as abatement is more expensive, production from REP sources is cheaper, electricity demand is less elastic to electricity price and the marginal environmental damage from GHG emissions rises.

*Proof.* Table 2.4 shows the sign of variation of the optimal levels of policy instruments when various parameters change[9]. A positive elasticity indicates a positive variation when a parameter increases, and an absolute elasticity smaller than one indicates that a 1% change in that parameter will cause a less than 1% change in the variable. We see that the elasticity of $\rho$ with respect to $\sigma_a$ and $\sigma_r$ is positive but smaller than 1, with respect to $\sigma_d$ it is negative but smaller than one and the elasticity with respect to $\delta$ is 1. The proof follows directly. □

The explanation of this result is straightforward: more REP should be installed when the environmental damage is higher, when REP are cheaper and

9. Elasticities have been calculated in Mathematica. The Mathematica notebook is available upon request from the contact author

when the other ways to reduce emissions, i.e. abatement and energy savings become more expensive. Similarly, a higher abatement cost naturally leads to a less stringent emission cap $\Omega$, while a higher marginal damage and a more elastic electricity demand (which means higher energy savings for a given change in electricity price) lead to a more stringent cap. The impact of cheaper REP on the optimal cap is ambiguous: on the one hand, it reduces the overall cost of cutting emissions, leading to a more stringent cap, but on the other hand it pushes to an increased use of the other policy instrument, the subsidy, which minors the importance of the emission cap.

Table 2.3 shows that in state –, there is no abatement, the carbon price is nil and the electricity price is solely determined by the supply curve, so the parameters considered in Table 2.3 have no effect on these variables. However, they have an indirect effect on $f_-$ and $r_-$ since they impact $\rho$. Hence, the considered parameters increase the amount of REP $r_-$ and they decrease the amount of fossil-fuel electricity $f_-$ when they increase the REP subsidy $\rho$.

In state +, as one could have expected, more abatements and a higher $CO_2$ price $\phi_+$ are triggered by a lower abatement cost, a more elastic electricity demand, more expensive REP, and a higher marginal damage. Moreover, a higher electricity price is triggered by a higher marginal damage, costlier REP, a more elastic electricity demand and, more surprisingly, a lower abatement cost. The explanation is that a lower abatement cost implies a more stringent target (Table 2.4), which in turn raises the electricity price in state +.

In state +, changes in energy production follow changes in the $CO_2$ price $\phi_+$: lower abatement costs, higher marginal damages and a more elastic electricity demand increase the $CO_2$ price, which in turn decrease the relative competitiveness of fossil fuel. In state –, the $CO_2$ price is nil and changes are more sensitive to the REP subsidy: higher abatement costs, higher marginal damages and a more elastic electricity demand increase the optimal REP subsidy, which in turn increase the relative competitiveness of REP.

Comparing Table 2.4 and Table 2.3 finally shows that the carbon price and the REP subsidy vary in opposite directions (except when the marginal damage changes). This can be seen in (2.12). If there is a risk that the carbon price equals zero in the low-demand state of the world, the mitigation efforts induced by the carbon price are no longer sufficient. An additional effort through REP production is necessary, induced by a strictly positive REP subsidy.

## 2.4 NUMERICAL APPLICATION: THE EUROPEAN ELECTRICITY SECTOR

### 2.4.1 Modified model

Having shown some analytical results with a model of a electricity sector alone, we turn to a slightly more complex model to show numerical results calibrated on the European electricity and allowance markets. In this section, we add an explicit allowance supply from non-electricity European Union Emission Trading System (EU-ETS) sectors. We therefore add a composite sector including all the other constrained emitters. The electricity producer can buy emission allowances ($e$) from the other constrained sectors on the allowance market to comply to the emission constraint. The other EU-ETS sectors are represented by their total abatement cost function, which has the following form:

$$AC_e = \frac{\sigma_e}{2} EE^2 - \begin{cases} \iota_e \, EE & \text{in state } + \\ 0 & \text{in state } - \end{cases}$$

where $\sigma_e$ is the slope of the aggregate non-electricity EU-ETS sector marginal abatement cost curve (MACC). The intercepts differ in the low demand and the high-demand state of the world. We assume there is a positive correlation between the level of electricity demand and the level of industrial activity. When the electricity demand is low, the industrial activity is also low and the allowance surplus is higher.

Next subsections will detail the data and assumptions made to calibrate the model. Some parameters being subject to a large uncertainty, we use a range of possible values for those parameters and discuss the distribution of results. For each uncertain parameter, we use a uniform probability distribution and we assume that these parameters are not correlated (except for the electricity demand and the industrial activity levels). Table 2.6 shows the minimum, median and maximum values of calibrated parameters resulting from the calibration process and used in the simulations.

We performed simulations with all possible combinations of parameters shown in Table 2.6, without any constraint on the carbon price. We tested the positivity of the carbon price, and if negative in the low-demand state, we conducted other simulations by constraining the carbon price to be equal to zero in the low-demand state. This distinguishes two qualitatively different simulation results. In the first category (subsequently called 2$^{nd}$ Best B), the carbon price is strictly positive in the low-demand state and the renewable energy power (REP) subsidy is nil. In the second category (subsequently called 2$^{nd}$ Best A), the carbon price is nil in the low-demand state and the REP subsidy is strictly positive. Appendix B.9 details the equations and solution of this model.

### 2.4.2 Data and assumptions for calibration

#### 2.4.2.1 *Supply functions*

The supply curves are tuned so as to match estimated long term marginal production costs functions. According to OECD (2010), the REP production break-even point starts at €80/MWh and goes up to €160/MWh. This marginal cost is rather a lower bound, as network and intermittency costs tend to raise it. We calibrated the REP supply function slope so as to reach the upper limit of the REP long-term marginal cost at a given percentage of a reference production level. This reference production level is taken equal to the electricity production from REP and fossil fuels in 2008, that is 2,060 TWh (ENERDATA 2013). For the maximal penetration rate of REP, we took a range of possible percentages, ranging from 10% to 50%. The fossil fuel long term supply curve, set at €80/MWh is tuned to an average European CCGT levelized cost of electricity, following OECD (2010).

#### 2.4.2.2 *Demand function*

The demand function has been calibrated so as to have a given price-elasticity when the demand equals the average between the 2008 and the 2009 reference production levels (2,060 TWh in 2008 and 1,929 TWh in 2009 (ENERDATA 2013)). We chose elasticities ranging from -0.1 to -0.5. The demand standard deviation Δ between the two states of the world was assumed to be close to the mean absolute deviation from the reference demand in 2008 and 2009. We chose values ranging from +50% to -50% of this value to account for the uncertainty on a possible future shock on demand. We assume each state of demand has a probability of $\frac{1}{2}$ to occur.

#### 2.4.2.3 *Abatement costs*

The slope of the MACC in the electricity sector has been calculated as follows: given an average $CO_2$ price of €22/t$CO_2$ in 2008, we assumed that fuel-switch allowed to abate a range of percentages of the total emissions of the electricity sector in 2008, ranging from 1 % to 5 %. This is in range with Ellerman and Buchner (2008), reporting an abatement of around 5% at a $CO_2$ price equal to €15/t$CO_2$. The MACC of the EU-ETS sector other than electricity was calibrated in the same way, by assuming a certain percentage of abatement in 2008 given the $CO_2$ price. We assumed abatements ranging from 1% to 5% for both sectors. The intercept of the MACC for non-electricity sectors in the low-demand state was calculated so as to obtain the difference of allowance over-allocation between 2008 and 2009 when the $CO_2$ price drops to zero (102 Mt$CO_2$ of allowance surplus in 2008, 241 Mt$CO_2$ surplus in 2009; data from Sandbag (2012). We took into account the perimeter of the EU-ETS combustion sector — which includes electricity and heat production — by adding the additional surplus allowances coming from the heat plants (41 Mt$CO_2$ according to Trotignon and Delbosc (2008)).

#### 2.4.2.4 *Additional parameters*

We took an average carbon intensity of 0.5 t$CO_2$/MWh for fossil production (IEA Statistics 2011), and a marginal damage between €10 and €30/t$CO_2$. The calibration presented in previous paragraphs is very cautious, considering demand and production levels already observed in 2008 and 2009. The increased regulatory risk induced by the introduction of the third EU-ETS phase and possible changes in the future Energy Efficiency Directive are captured through changing the standard deviation of demand and emission surplus from the non electricity EU-ETS sector.

Table 2.5 synthesizes the range of values used for all parameters subject to a large uncertainty.

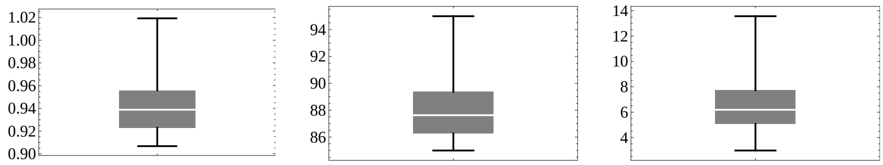
### 2.4.3 Optimal policy instruments and $CO_2$ price levels

With the parameter ranges shown in Table 2.6, 50.9% of the simulations display a nil carbon price in the low-demand state and a strictly positive REP subsidy. Figure 2.2 illustrates Proposition 2.1. It shows box whisker plots of the optimal emission cap $\Omega^{\star}$ (Fig. 2.2a) and the optimal REP subsidy $\rho^{\star}$ (Fig. 2.2b) in all simulations with a 2nd Best instrument setting (mix $M_2^n$) and a nil carbon price in the low-demand state. Figure 2.2c shows a box whisker plot of the expected $CO_2$ price.

The optimal emission cap ranges from 0.91 to 1.02 Gt$CO_2$, and the optimal subsidy ranges from €2.68/MWh to €9.93/MWh. The optimal expected $CO_2$ price ranges from €2.97/t$CO_2$ to €13.6/t$CO_2$. As a comparison, the actual cap calculated by Trotignon and Delbosc (2008)) amounts to 1.05 Gt$CO_2$,

**Table 2.5:** Ranges of parameters used in the numerical simulations for calibration purposes. All possible combinations of parameters were successively simulated.

| Description | Dimension | Range |
|---|---|---|
| Marginal environmental damage | (€/$tCO_2$) | (10,20,30) |
| Price-elasticity of demand (absolute value) | 1 | (0.1,0.2,...,0.5) |
| Abatement from the aggregate EU-ETS sector for 15 €/$tCO_2$ | (%) | (1,2,...,5) |
| Abatement from the power sector for 15 €/$tCO_2$ | (%) | (1,2,...,5) |
| Maximum share of REP in the energy mix | (%) | (10,20,...,50) |
| Standard deviation of demand | (TWh) | (33,49...,98) |




**(a)** Optimal emission cap ($GtCO_2$).
**(b)** Optimal REP tariff (subsidy + wholesale price) (€/MWh RE).
**(c)** Expected $CO_2$ price (€/$tCO_2$).

**Figure 2.2:** Box whisker plots of the optimal instrument values and expected $CO_2$ price for all simulations with a 2nd Best instrument setting (mix $M_2^n$) and a nil carbon price in the low-demand state of the world.

the actual REP tariff range from €50/MWh to €90/MWh in France and Germany and since summer 2011, the $CO_2$ price has been in the range (€3/$tCO_2$-€13/$tCO_2$). The relatively low levels of both the expected $CO_2$ price and the REP subsidy are due to the fact that it is a linear combination of both that equals the marginal damage (see (2.12)). These values cannot necessarily be directly compared to actual subsidy levels since the latter account for all positive externalities expected from REP support.

### 2.4.4 Expected welfare gains from adding a REP subsidy

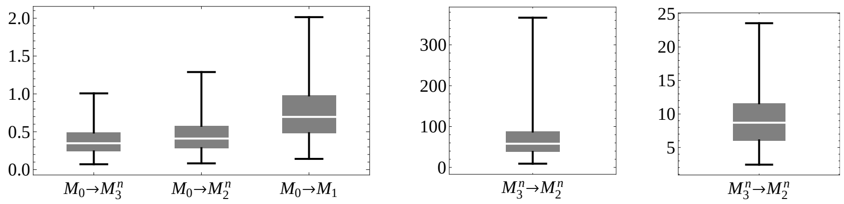
In order to evaluate the gains from adding a subsidy to the EU-ETS, we compute the expected welfare differences between simulations with different instrument mixes. We compare four settings:

- A first-best instrument mix ($M_1$), with a unique $CO_2$ price across all states of the world;
- A second-best instrument mix ($M_2$), with an EU-ETS and a REP subsidy;
- A third-best instrument mix ($M_3$), with an EU-ETS alone and a nil $CO_2$ price in the low-demand state.
- A business-as-usual setting ($M_0$), with no policy at all.

The gain — or welfare difference — is calculated as the drop in environmental damages minus mitigation costs. Fig. 2.3 shows box whisker plots of the expected welfare gains from adding a given instument mix compared to the business-as-usual (BAU) setting ($M_0$ to $M_3$, $M_0$ to $M_2$, $M_0$ to $M_1$) in all

**Table 2.6:** Values of the calibrated parameters.

| | Units | Description | Min | Med. | Max |
|---|---|---|---|---|---|
| $\sigma_a$ | (€/$MtCO_2{}^2$) | Slope of the power sector MACC | 0.44 | 0.81 | 2.2 |
| $\sigma_e$ | (€/$MtCO_2{}^2$) | Slope of the rest-of-EU-ETS MACC | 0.52 | 0.95 | 2.61 |
| $\sigma_d$ | ($GWh^2$/€) | Slope of the demand function | 2.58 | 6.7 | 12.9 |
| $\sigma_r$ | ($GWh^2$/€) | Slope of the RE supply function | 2.49 | 6.43 | 12.5 |
| $\delta$ | (€/$tCO_2$) | Marginal environmental damage | 10 | 15.3 | 30 |
| $\Delta$ | (TWh) | Variance of demand | 32.8 | 69.6 | 98.3 |
| $\tau$ | ($tCO_2$/MWh) | Average carbon intensity of fossil fuel-based electricity | 0.5 | 0.5 | 0.5 |
| $\lambda$ | - | Probability of the high-demand state | 0.5 | 0.5 | 0.5 |
| $\iota_f$ | (€/MWh) | Intercept of the fossil fuel supply function | 80 | 80 | 80 |
| $\iota_r$ | (€/MWh) | Intercept of the RE supply function | 80 | 80 | 80 |
| $\iota_d$ | (G€/MWh) | Intercept of the demand function | 2.19 | 2.51 | 2.99 |
| $\iota_{e+}$ | (€/$tCO_2$) | Intercept of the rest-of-EU-ETS MACC (state +) | 94.6 | 173 | 473 |
| $\iota_{e-}$ | (€/$tCO_2$) | Intercept of the rest-of-EU-ETS MACC (state –) | 0 | 0 | 0 |

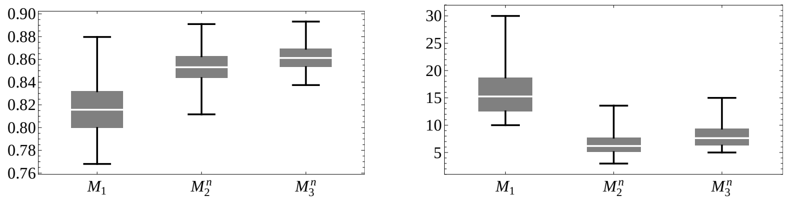



**(a)** Welfare gains in bn €.

**(b)** W. gains of adding a subsidy in million €.

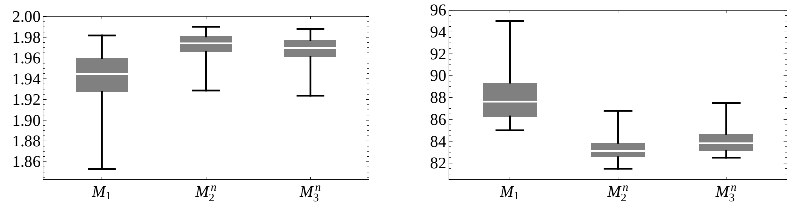
**(c)** W. gains of adding a subsidy in % of $M_0 \rightarrow M_1$ gains.

**Figure 2.3:** Box whisker plots of expected welfare gains from adding a given instrument mix to a BAU setting with no instrument ($M_0 \rightarrow M_3^n$, $M_0 \rightarrow M_2^n$, $M_0 \rightarrow M_1$) in bn €, and of expected welfare gains from adding a REP subsidy to an EU-ETS ($M_3^n \rightarrow M_2^n$) in million € and in percentage of the expected gains from a carbon tax, in all scenarios where the $CO_2$ price is nil in the low-demand state of the world.




**(a)** Expected emissions ($GtCO_2$).

**(b)** Expected $CO_2$ price (€/$CO_2$).




**(c)** Expected energy production (TWh).

**(d)** Expected price (€/MWh).

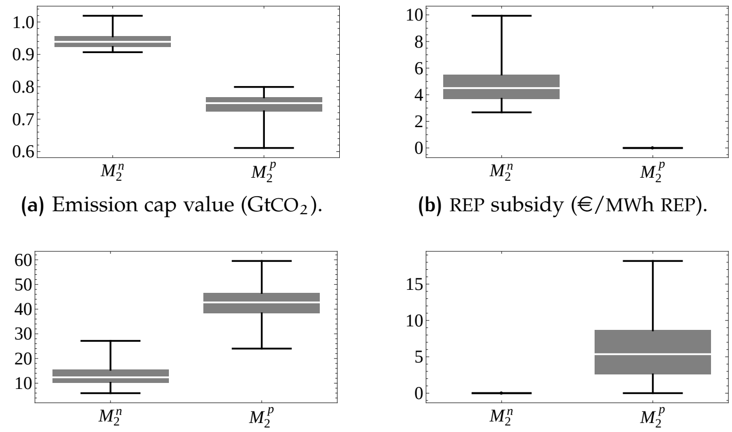
**Figure 2.4:** Box whisker plots of the expected values of various variables in simulations $M_1$ (carbon tax), $M_2^n$ (EU-ETS + REP subsidy) and $M_3^n$ (EU-ETS alone) when the $CO_2$ price is nil in the low-demand state.

scenarios where uncertainty is such that the $CO_2$ price turns out to be nil in the low-demand state of the world.

Compared to a BAU setting with no instrument (mix $M_0$), The gains from having an EU-ETS and a REP subsidy if there is a risk that the $CO_2$ price equals zero in the low-demand state are quite important, ranging from more than €1.4 billion to several hundred million €. The gains from adding a REP subsidy to an EU-ETS range from ca. €10 million to several hundred million €. They represent from approximately 3% to 24% of the gains one could expect from a first-best carbon tax.

### 2.4.5 Expected emissions, productions and prices with various instrument mixes

Following our analysis in section 2.3 and illustrating Proposition 2.3, the Fig. 2.4 presents box whisker plots of expected values of different variables in the simulations with a nil $CO_2$ price in the low-demand state (superscript n). We computed those values with a 1st Best instrument mix (a carbon




**(a)** Emission cap value ($GtCO_2$). **(b)** REP subsidy (€/MWh REP).

**(c)** $CO_2$ price in the high-demand state (€/$tCO_2$). **(d)** $CO_2$ price in the low-demand state (€/$tCO_2$).

**Figure 2.5:** Box whisker plot of various instrument levels and $CO_2$ price in simulations $M_2^n$ (EU-ETS + REP subsidy and a nil $CO_2$ price in the low-demand state) and simulations $M_2^n$ (EU-ETS + REP subsidy and a strictly positive $CO_2$ price in the low-demand state).

tax, labeled $M_1$), with a 2nd Best setting (EU-ETS + subsidy, labeled $M_2^n$) and in a 3rd Best setting (EU-ETS alone, labeled $M_3^n$). Figure 2.4a presents the expected emissions, Figure 2.4b the expected $CO_2$ price, Figure 2.4c the expected energy production and Figure 2.4d the expected wholesale price.

Consistently with Proposition 2.3, Figure 2.4a shows that expected emissions are lower in the $M_2^n$ setting than in the $M_3^n$ setting, and the lowest in the $M_1$ setting. The expected $CO_2$ price is the lowest in the $M_2^n$ setting. As a result, the wholesale price is also the smallest in the $M_2^n$ setting, but expected energy production is the highest.

### 2.4.6 Shift in the optimal emission cap and $CO_2$ price

In order to discuss the optimization behavior of the social planner, we analyze the optimal instrument levels and carbon price in the second-best setting (labeled $M_2$) for all parameter combinations. For each combination, the uncertainty on the electricity demand is either low enough to get an optimal emission cap that is binding in both states of demand ($M_2^p$), either too high and implies a nil $CO_2$ price in the low-demand state of the world ($M_2^n$). We then compare the two groups of simulations and show the results as box whisker plots in Fig. 2.5. Fig. 2.5a shows the optimal emission cap for all parameter combination, Fig. 2.5b the REP subsidy, Fig. 2.5c the $CO_2$ price in the high-demand state of the world and Fig. 2.5d the $CO_2$ price in the low-demand state of the world.

As already discussed in section 2.2, Fig. 2.5a shows a higher emission cap in all $M_2^n$ scenarios. This is due to the fact that when the $CO_2$ price turns out to be nil in the low-demand state, no additional mitigation effort is made in this state and the cap is optimized *ex-ante* on the high demand level. Fig. 2.5b, 2.5c and 2.5d illustrate Proposition 2.2. If there is a risk that the $CO_2$ price equals zero as for all $M_2^n$ scenarios in Fig. 2.5d, there is a strictly positive subsidy ($M_2^n$ scenarios in Fig. 2.5b) and the $CO_2$ price in the high-demand state of the world drops compared to $M_2^p$ scenarios(Fig. 2.5c).

## 2.5 DISCUSSION AND CONCLUSION

We bring a new contribution to the analysis of the coexistence of several policy instruments to cover the same emission sources. We find that optimizing simultaneously an European Union Emission Trading System (EU-ETS) and e.g. a subsidy to renewable energy power (REP) can improve the welfare compared to a situation with the EU-ETS alone, especially if uncertainty on the level of electricity demand (and hence on the abatement costs) is high enough. In a context of a very low $CO_2$ price and large anticipated surplus on the EU-ETS at least until 2020, these findings justify the addition of other policy instruments aiming at reducing $CO_2$ emissions covered by the EU-ETS to a possible future revision of the emission cap.

We find that under a reasonable set of parameters, defining simultaneously an emission cap and an overlapping policy instrument, such as a REP subsidy of about €2.7/MWh to €9.9/MWh (corresponding to a tariff ranging from €85/MWh to €95/MWh) can improve welfare by about 2.4% to 23.6% of the total gain of a carbon tax, that is about €9 million/yr to €366 million/yr. This gain is obtained through $CO_2$ emission reductions alone and does not rely on additional market failures or externalities. The addition of a REP subsidy also increases the total energy production, decreases the electricity price and the $CO_2$ price and reduces the total expected emissions. Our results are in line with existing literature concerning the decreasing effect of a REP subsidy on the carbon price when it is combined with an emission cap. We however find that under certain circumstances, interactions between a subsidy and an emission cap can reduce emissions and improve welfare, compared to an emission cap alone.

On a more methodological note, our results invite to deepen the reflection on the role of uncertainty. Noticeably, they highlight the possibility of corner solutions (in this case, a zero $CO_2$ price), when comparing policy instruments and policy packages. In addition to showing that an optimal policy mix to reduce $CO_2$ emissions can contain more than one instrument, we find several key analytical results that qualitatively differ from the literature. For instance, expected emissions are no longer equivalent between policy instruments, even with an additive uncertainty on the marginal abatement cost (MAC), and the optimal emission cap no longer depends on all states of nature but only on the high-demand one.

Our results are based on the assumption that the risk of the $CO_2$ price dropping to zero cannot be excluded. The history of many cap-and-trade systems, including the US acid rain program, Regional Greenhouse Gases Initiative (RGGI) and the EU-ETS fully justifies this assumption, since the allowance price has dropped to virtually zero (or to the floor price) in all these systems. Moreover, uncertainty on the $CO_2$ price does not only stem from the business cycle, as in our model, but also from uncertainty on future policies, such as the Energy Efficiency Directive whose implementation is currently debated in the European Union (EU). Our analysis brings some economic insight into the debate about the future European policy mix and about whether it is justified or preferable to complement a future revision of the EU-ETS cap with an overlapping instrument.

While developping REP is a valuable option to mitigate emissions, our results could be obtained with any instrument giving an incentive to reduce emissions in states of the world with low demand levels. Instruments promoting energy efficiency could be equally efficient, provided the actual energy consumption reduction is calculated against the right baseline. One could imagine instruments being more efficient in low-demand states than in high-demand states where mitigation is already incentivized by the positive carbon price, such as efficiency standards based on the mitigation effort. It is hard however to imagine how such instruments would work in practice. Moreover, we explore only one channel of potential interactions, namely uncertainty combined with the unavailability of a carbon tax. Other justifications and effects should be considered when trying to give an accurate picture of the potential efficiency of an instrument addition to the EU-ETS, such as learning or innovation considerations and dynamic or general equlibrium effects for example.

Complementing an EU-ETS with price-like features, such as an auction reserve price or a price floor as argued by Fankhauser et al. (2010) would bring the necessary incentives in the low-demand state. Our results depend however on the second-best framework implied by an inefficient EU-ETS. Optimizing an auction price or a floor price along with the emission ceiling, as in our model, would effectively allow to get back to a first-best framework by imposing a floor at the Pigovian level. If on the contrary one assumes the $CO_2$ price, the floor price or the auction reserve price to be "too low" (i.e. below the Pigovian level), as does Hoel (2012), our framework becomes relevant again and an additional instrument becomes welfare-improving.

Further aspects could be worth investigating. Modeling banking across trading periods with periodic renegotiation of the cap could mitigate the sub-optimality of the EU-ETS hence the room for complementary policies, but it would seriously complicate the analysis without necessarily providing new insights. Assuming other sources of uncertainty, such as technological or regulatory uncertainty could also have an effect on the outcome, depending on the probability associated with a nil carbon price. Finally, we focus our analysis on one channel of positive interactions between several mitigation instruments. Completing the picture by incorporating other market failures could bring useful insights on the benefits brought by adding a mitigation instrument to the EU-ETS.

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# 3 PHASING OUT DIRTY CAPITAL: ASSESSING AND ORDERING INVESTMENT IN LOW- AND ZERO-CARBON CAPITAL [1]

## 3.1 INTRODUCTION

The European Union aims at decarbonizing almost completely the power sector by 2050 (EU 2011). This requires that the preexisting carbon-intensive capital is replaced by one or several types of long-lived and greener capital. Cutting emissions from existing coal power plants can for instance be achieved by building gas power plants (gas is less carbon-intensive than coal), or often more-expensive but almost-carbon-free options such as nuclear or renewables (hydro, wind, solar, biomass). [2] The use of different types of low-carbon capital running on different types of fossil fuels for the transition raises two main challenges:

- What is the optimal timing of investment and production to phase out the preexisting carbon-intensive technologies?
- How to assess the cost-efficiency of this transition?

We find that taking congestion costs (in the form of convex investment costs) into account is essential when assessing the phasing out of all preexisting carbon-intensive capacities. Congestion accounts for the fact that preexisting capital cannot be replaced at once, and captures the increasing opportunity cost to use scarce resources (skilled workers and appropriate capital) in order to build more green capacities. Increasing the speed of investment is only possible at an increasing marginal cost.

We find that depending on these congestion effects, investment in green technologies may not follow an intuitive ranking. For instance, expensive renewable power may be used to phase out dirty coal before lower-cost gas power plants start to be built. Moreover, it may be optimal to build large amounts of gas power plants, and leave them partly unused before they depreciate (a process known as *early scrapping*).

We investigate the use of long term marginal costs, or *levelized costs* to assess investment in each technology, i.e. the ratio of discounted costs of installing and using the technology, over discounted production during its lifetime — including the cost of greenhouse gases (GHG) emission. In energy textbooks and studies, for instance, the levelized cost of electricity (LCOE) is used to compare various types of power plants (e.g. Alok 2011, Branker et al. 2011, Kost et al. 2012, EIA 2013, IPCC 2007) for given investment costs and for a given number of operating hours per year. An accepted rule of thumb is that technologies that produce at a lower levelized cost are superior. It is not clear whether the levelized costs define a merit order, i.e.

1. This chapter has been coauthored with Adrien Vogt-Schilb, PhD student at CIRED. It is a modified version of a CIRED working paper (Lecuyer and Vogt-Schilb 2013).

2. This paper focuses on the electricity sector for clarity, but the results could be applied with only small adaptations to the transportation sector, who faces similar challenges. In order to reduce emissions from transportation by two thirds below the 1990 level by 2050, legacy inefficient thermal vehicles can be replaced by more-efficient thermal vehicles, or more-expensive but less-emitting plug-in hybrids and electric vehicles.

whether "lower-cost" technologies should be built first, and "higher-cost" technologies should wait that the carbon price is sufficiently high to become competitive.[3]

We find that optimal LCOEs are not equal between technologies, and not equal to the output price, contrary to what textbook say, even when they account for emission and resource costs, because they do not take congestion effects into account. In the numerical application to the European electricity sector, we find that the optimal LCOE of wind is higher than the optimal LCOE of gas. LCOEs account for GHG emissions and variable energy costs, but assume investment costs are constant. Because investment costs are convex, investing early reduces the discounted cost of the transition, and the optimal long-term technology mix has consequences on optimal short-term efforts. Here, wind capacities are built faster, and their investment drops also faster than gas. As a result, using LCOE to assess wind investment is a greater approximation than for gas, and its LCOE is higher.

Our results suggest that in the European electricity sector, decisions taken by comparing the levelized costs of various technologies would favor intermediate technologies (e.g. gas plants) to the detriment of more-expensive but lower-carbon technologies (renewable power), leading to a suboptimal investment schedule.

At our best knowledge, the literature lacks a theoretical model to assess the optimal cost and timing of investment in different types of low-carbon capital. A related question is however treated by Vogt-Schilb et al. (2012). They consider a social planner who accumulates one type of carbon-free capital in several sectors to meet a carbon budget at the lowest discounted cost. They find that the optimal cost and timing of GHG reductions differ considerably from those obtained with more classic models relying on abatement cost curves. More precisely, capital accumulation means that: (i) abatement (in $tCO_2/yr$) start later than generally found — less abatement in the short term and more abatement in the long term — and (ii) optimal economic efforts — i.e. investment — to curb emissions (in $/yr) are concentrated over the short-term and decrease in time. They do not represent several types of low-carbon capital within a sector however, nor consider any demand constraint applying to all technologies.[4]

The remaining of the paper is structured as follows: we describe the model in Section 3.2. In Section 3.3 we derive the first-order conditions and discuss the equimarginal principle. Section 3.4 characterizes the various phases of the investment dynamics. In Section 3.5 we calibrate our model with data from the European electricity sector. Section 3.6 concludes.

3. Of course, the *levelized costs* provide only part of the relevant information to assess different technologies. In particular, ranking technologies according to their levelized costs leaves aside any benefits of early investment from learning by doing (LBD) effects. However, several existing studies suggest that those effects are negligible. Goulder and Mathai (2000) investigate the impact of LBD on the optimal timing of GHG reductions in an aggregated model and find little difference with the simulation without LBD. Fischer and Newell (2008) investigate the optimal costs of producing electricity from renewable power subject to LBD and find that justifies only a 10 % increase in the optimal cost.

4. Beginning with an early suggestion by van der Ploeg and Withagen (1991), other contributions study the link between low-carbon capital accumulation and the optimal timing of GHG emission reductions. Among them, Fischer et al. (2004) study the optimal carbon tax in a model where clean capital accumulation reduces GHG emissions and environmental damages lower current welfare. Gerlagh et al. (2009) and Acemoglu et al. (2012) add knowledge accumulation to a similar framework. Rozenberg et al. (2013) study the intertemporal distribution of abatement efforts implied by several mitigation strategies (under-using existing brown capital or focusing on emissions embedded in new capital) to meet an emission ceiling constraint.

## 3.2 MODEL

A social planner controls the supply of electricity, referred to as *output* in this article. It builds green capacity, which emits less GHG than preexisting high-carbon technologies — e.g. coal power stations — treated as an aggregated overabundant dirty backstop. It uses green and preexisting brown capacities to meet an exogenous inelastic demand, and cope with a given carbon budget.

### 3.2.1 Investing in and using capital

At each time $t$, the social planner chooses positive investment $x_{i,t}$ in a set of technologies indexed by $i$. The investment adds to the installed capacity $k_{i,t}$, which otherwise depreciates at the constant rate $\delta$ (dotted variables denote temporal derivatives):

$$\dot{k}_{i,t} = x_{i,t} - \delta k_{i,t} \tag{3.1}$$

$$x_{i,t} \geqslant 0 \tag{3.2}$$

Without loss of generality,[5] we assume green capacities are nil at the beginning ($k_{i,t=0} = 0$). Investment is made at a cost $c_i(x_{i,t})$ assumed increasing and convex ($c_i' > 0, c_i'' > 0$). This captures the increasing opportunity cost to use scarce resources (skilled workers and appropriate capital) in order to build more green capacities.[6]

The social planner then chooses how much output to produce from each technology. We assume that the production process exhibits constant returns to scale: two gas plants can produce twice the power that one gas plant can produce. The positive production $q_{i,t}$ with technology $i$ cannot exceed the installed capacity $k_{i,t}$:

$$0 \leqslant q_{i,t} \leqslant k_{i,t} \tag{3.3}$$

We define the utilization rate $u_{i,t}$ as the ratio of production over installed capacity:

$$u_{i,t} = \frac{q_{i,t}}{k_{i,t}} \tag{3.4}$$

We assume that overabundant brown capital is inherited at the beginning of the period (e.g, inefficient coal plants). At each point, the total production (including from preexisting brown technologies) has to meet an exogenous demand $D$ assumed constant for simplicity:

$$\sum_i q_{i,t} = D \tag{3.5}$$

5. A initial situation with existing green capacities can be tackled simply by scaling down the total capacity to be phased out: green capacities replace only the preexisting emitting capital. In Section 3.5 we tackle the case of the European electricity sector with preexisting low-carbon capacity.

6. Unlike Vogt-Schilb et al. (2012), we allow investment made infinitesimally slowly to be costly: $c_i'(0) > 0$.

### 3.2.2 Carbon budget

Let $R_i$ be the carbon intensity (or emission rate) of technology $i$. The stock of cumulative emissions $m_t$ grows with emissions $R_i\, q_{i,t}$:

$$\dot{m}_t = \sum_i R_i\, q_{i,t} \tag{3.6}$$

The social planner is subject to a so-called carbon budget, i.e., cumulative emissions cannot exceed a given ceiling $\bar{M}$:

$$m_t \leqslant \bar{M} \tag{3.7}$$

Cumulative emissions have been found to be a good proxy for climate change (Allen et al. 2009, Matthews et al. 2009).[7] Some policy instruments, such as an emission trading scheme with unlimited banking and borrowing, set a similar constraint on firms.

### 3.2.3 Low and zero-carbon technologies

For analytical tractability, we assume the social planner can choose only two green technologies: a fossil-fueled low-carbon technology (LCT), labeled $\ell$ in subscripts and an inexhaustible zero-carbon technology (ZCT), labeled $z$ in subscripts.

The ZCT (e.g, renewable power) is completely carbon-free.

$$R_z = 0 \tag{3.8}$$

We model a single preexisting high-carbon technology (HCT), labeled $h$ in subscripts, representing e.g. coal power, assumed to be more carbon-intensive than the low-carbon technology:

$$R_h > R_\ell > 0 \tag{3.9}$$

We assume that low-carbon capacity is cheaper than zero-carbon capacity in the sense that:

$$\forall x \quad c'_\ell(x) < c'_z(x) \tag{3.10}$$

Investment $xit$ is assumed to be in full capacity equivalent, meaning that we assume each unit of capacity installed produces at full rate.[8] Production from the HCT and the LCT requires to buy fossil fuels at an exogenous cost $\alpha_i$, assumed constant for simplicity, so that the total cost function equals:[9]

$$\forall i, t \quad \mathcal{C}_{i,t} = c_i(x_{i,t}) + \alpha_i \cdot q_{i,t} \tag{3.11}$$

Finally, we focus on the case where the ceiling on GHG concentration is binding. This corresponds for instance to a case where $h$ represents coal, too abundant to reach the 2°C target.

---

7. Many models assume the atmospheric carbon naturally decays at a constant rate. We chose not to include this to keep the analysis as simple as possible. Physical models suggest moreover that such an assumption is incompatible with the carbon cycle as it is known.

8. The numerical version of the model tries to capture some of the intermittency issues of renewables by adding an average load factor. The analytical model is however kept as simple as possible.

9. An interesting extension would be to consider endogenous resource costs, coming from the scarcity of an exhaustible stock of resources.

| | Description | Power |
|---|---|---|
| $i$ | technology index | |
| $h$ | high-carbon technology (HCT) | |
| $l$ | low-carbon technology (LCT) | |
| $z$ | zero-carbon technology (ZCT) | |
| $k_{i,t}$ | capacity of technology $i$ at time $t$ | GW |
| $q_{i,t}$ | production of technology $i$ at time $t$ | GW |
| $x_{i,t}$ | investment in technology $i$ at time $t$ | GW/yr |
| $\nu_{i,t}$ | shadow price of new capacities $i$ | \$/(GW· yr) |
| $\mu_t$ | present cost of emissions | \$/t$CO_2$ |
| $\alpha_{i,t}$ | present cost of resource used by technology $i$ | \$/MWh |
| $\gamma_{i,t}$ | shadow rental cost of existing capacity $i$ | \$/(GW· yr) |
| $\omega_t$ | output price | \$/GWh |
| $c_i(\cdot)$ | investment costs in technology $i$ | \$/yr |
| $m_t$ | stock of atmospheric carbon | t$CO_2$ |
| $\delta$ | depreciation rate | $yr^{-1}$ |
| $r$ | discount rate | $yr^{-1}$ |
| $R_i$ | emission rate of technology $i$ | t$CO_2$/GWh |
| $\bar{M}$ | carbon budget | t$CO_2$ |
| D | Demand | GW |

**Table 3.1**: Variables and parameters notations used in the model. The last column gives possible units for the electricity sector.

### 3.2.4 Social planners program

The program of the social planner consists in determining the trajectories of investment $x_{i,t}$ and production $q_{i,t}$ that minimize discounted costs while satisfying the demand D and complying with the carbon budget $\bar{M}$ ($r$ is the constant discount rate and the Greek letters in parentheses are the costate variables and Lagrange multipliers):

$$\min_{x_{i,t},q_{i,t}} \int_0^\infty e^{-rt} \sum_i c_i(x_{i,t}) + \alpha_i \cdot q_{i,t} dt \tag{3.12}$$

$$\begin{aligned}
\text{s.t. } \dot{k}_{i,t} &= x_{i,t} - \delta k_{i,t} && (\nu_{i,t}) \\
q_{i,t} &\leqslant k_{i,t} && (\gamma_{i,t}) \\
\sum_i q_{i,t} &= D && (\omega_t) \\
q_{i,t} &\geqslant 0 && (\lambda_{i,t}) \\
x_{i,t} &\geqslant 0 && (\xi_{i,t}) \\
\dot{m}_t &= \sum_i R_i \, q_{i,t} && (\mu_t) \\
m_t &\leqslant \bar{M} && (\eta_t)
\end{aligned}$$

Notations are gathered in Table 3.1.

## 3.3 SIMPLIFIED FIRST-ORDER CONDITIONS AND THE EQUIMARGINAL PRINCIPLE

When production and investment are strictly positive, the multipliers associated with their respective positivity constraints are nil, and first-order conditions simplify to (see C.2 for the complete equation set):

$$c_i'(x_{i,t}) = -e^{rt}\nu_{i,t} \tag{3.13}$$

$$\dot{\nu}_{i,t} - \delta\nu_{i,t} = \omega_t - \mu_t R_i - \alpha_{i,t} \tag{3.14}$$

These simplified FOCs simply state that the marginal investment cost is equal to a value $(\nu_{i,t})$ that depends on the resource costs $(\alpha_{i,t})$, the carbon costs $(\mu_t R_i)$ and the variable cost of the marginal technology $(\omega_t)$ through a differential equation depicting the natural depreciation of capacities.

The simplified FOCs imply that when production and investment are strictly positive, the optimal investment schedules $x_{i,t}$ satisfy the following differential equation: [10]

$$(\delta + r)\ c_i'(x_{i,t}) - \frac{d}{dt} c_i'(x_{i,t}) = e^{rt}\ \ (\omega_t - \mu_t\, R_i - \alpha_{i,t}) \tag{3.15}$$

The left hand side of (3.15) corresponds to what Vogt-Schilb et al. (2013) have called the *marginal implicit rental cost of capital* (marginal implicit rental cost of capital (MIRCC)), extending the concept proposed by Jorgenson (1967) to the case of endogenous capacity prices. It corresponds to the efficient market rental price of capacities, where capitalists would be indifferent between: (i) buy capital at $t$ at a cost $c_i'(x_{i,t})$, rent it out during one period $dt$ at a price $p_{i,t}$, and sell the depreciated ($\delta$) capacities at $t + dt$ at a price $c_i'(x_{i,t}) + \frac{d}{dt} c_i'(x_{i,t})dt$ or (ii) simply lend money at the interest rate $r$. Appendix C.1 details another intuition behind this concept.

The right hand side of (3.15) relates to the variable costs and revenues of a producer. The output is sold at its current price $e^{rt}\ \omega_t$. [11] Producing one unit of the output requires to use fuel bought at the current price $\alpha_{i,t}\ e^{rt}$ and pay for the emitted carbon $R_i$ (3.6) at the current price $\mu_t\, e^{rt}$.

Equ. (3.15) can be seen as an application of the equimarginal principle. It provides a simple rule to arbitrate *production* decisions at each moment, by relating the output price, the rental cost of productive capacities and the variable costs. As the equimarginal principle applies to the decision of renting the capital, it does not directly describe trade-offs for *investors*.

### 3.3.1 Optimal marginal investment costs when production and investment are positive

The optimal investment trajectory are the solution of the differential equation (3.15). [12] If production and investment are strictly positive during a

10. (3.13)$-\delta \frac{d}{dt}$(3.13) leads to $e^{rt}\ (\dot{\nu}_{i,t} - \delta\nu_{i,t}) = (\delta + r)\ c_i'(x_{i,t}) - \frac{d}{dt} c_i'(x_{i,t})$; substituting in (3.14) leads to the desired result.

11. $\omega_t$ can be interpreted from a certain perspective as the output price, as it is the shadow cost of the demand constraint. The demand being really an obligation to produce, it corresponds formally to the variable cost of the marginal production technology, or in other terms to the variable cost of the last most expensive unit of capacity not used (see (C.10)). Comparably, being the shadow cost of the carbon budget constraint, $\mu_t$ can be interpreted as the carbon price (see C.18).

12. Note that it still does not result in a simple *static* criteria for investment, to compare two technologies. At a given point in time, one does not know in which technology he should invest: the optimal marginal investment costs (MICs) of one technology can be superior or inferior to the other.

time interval $(\sigma_i, \tau_i)$, the optimal MIC $\mathrm{d}ci$, defined as the instantaneous cost of investing in one additional unit of capacity (in full capacity equivalent), can be expressed as a sum of two terms:

- the present value of all future revenues from selling the output minus costs from emission and resource usage $(\omega - \mu\, R_i - \alpha_i)$ produced by the depreciated marginal unit of capacity $(e^{-\delta(t-\theta)})$, plus
- a term expressing the end-of-game value of the unit of capacity installed, tending toward $c_i'(x_{i,\tau_i})$:

$$\forall t \in (\sigma_i, \tau_i), \qquad (3.16)$$

$$c_i'(x_{i,t}) = e^{rt} \int_t^{\tau_i} e^{-\delta(t-\theta)} (\omega_\theta - \mu_\theta\, R_i - \alpha_{i,\theta}) \mathrm{d}\theta + e^{(r+\delta)(t-\tau_i)} c_i'(x_{i,\tau_i})$$

C.5 shows that (3.16) is the textbook solution of (3.15). As can be seen in Fig. 3.1, (3.16) can be seen as a generalization of the previous finding by Vogt-Schilb et al. (2012) that when abatement is obtained by accumulating low-carbon capital, optimal efforts to curb emissions are not necessarily growing over time.

### 3.3.2 Levelized Cost Of Electricity

Equ. (3.16) gives a general relation between the optimal MIC and a discounted sum of future revenues during a time period when capacities are used. In practice, an investment decision at time $t$ relies upon the anticipation of all future cash flows. Levelized costs of electricity (LCOEs) are frequently used to compare different technologies in the power sector, with the underlying idea that technologies with lower LCOEs are cheaper, hence superior, to technologies with higher LCOEs (e.g. Alok 2011, Kost et al. 2012, EIA 2013, IPCC 2007). [13]

DEFINITION 3.1. The levelized cost of electricity (LCOE), denoted $\mathcal{L}_{i,t}$, is the ratio of discounted costs to discounted production of the marginal capacity (we express them in present value):

$$\mathcal{L}_{i,t} = \frac{e^{-rt} c_i'(x_{i,t}) + \int_t^\infty (\mu R_i + \alpha_{i,\theta})\, u_{i,\theta}\, e^{-\delta_i(\theta-t)}\, \mathrm{d}\theta}{\int_t^\infty u_{i,\theta}\, e^{-(r+\delta_i)(\theta-t)}\, \mathrm{d}\theta} \qquad (3.17)$$

The total costs from the marginal capacity built at $t$ express as the investment cost $c_i'(x_{i,t})$, plus the variable costs $(\mu R_i + \alpha_{i,\theta})$ associated with the marginal capacity along its lifetime (during which it will depreciate at the rate $\delta_i$ and will be used at a rate $u_{i,\theta}$ (3.21)). The denominator is the discounted production of the depreciating marginal unit of capacity over time. A question is whether the LCOE may be used as a good proxy to assess investment decisions.

## 3.4 ANALYTICAL RESULTS

### 3.4.1 Assessing investment in carbon-intensive and zero-carbon capital

Assessing in detail investment decisions and ordering investment in green production technologies requires to characterize completely the optimal MICs,

13. C.3 discusses the definition of levelized costs in a static framework.

hence the various phases defined by the slackness conditions (notably the time period $(\sigma_i, \tau_i)$ of (3.16)): [14]

1. In a first phase (for $t \in [0, T_\omega]$) HCT production decreases (compensated by the increasing total production of LCT and ZCT). The output price equals the (constant) emission costs plus the resource costs from the high-carbon technology: $\omega_t = \mu R_h + \alpha_h$.
2. In the second phase ($t \in [T_\omega, T_\gamma]$), LCT production decreases slower than the natural rate of replacement of its capacity. Investment in LCT continues even if its production decreases ($x_{\ell,t} < \delta k_{\ell,t}$). From $T_\omega$ on, (for $t \in [T_\omega, T]$) LCT production decreases and ZCT production increases (LCT production may decrease before $T_\omega$).
3. In a third phase (for $t \in [T_\gamma, T]$) LCT production decreases faster than the natural depreciation rate of its capacity. The output price equals the sum of constant resource costs and constant emission costs from the low-carbon technology: $\omega_t = \mu R_\ell + \alpha_\ell$.
4. At T, the system reaches a steady state, all production comes from the ZCT, emissions are nil, atmospheric pollution is at its ceiling. If low-carbon resources were binding they are exhausted at T ($\alpha_{\ell,T} S_{\ell,T} = 0$).

PROPOSITION 3.1. When the social planner invests in both the ZCT and the LCT, it builds zero-carbon capacity at a higher marginal investment cost (in full capacity equivalent) than low-carbon capacity.

*Proof.* Using previous results, the optimal MIC for the LCT and the ZCT can be expressed as a function of the carbon price and the resource costs during the different phases, refining the general expression given by Eq. 3.16:

$$\begin{aligned}\forall t \geqslant T_z, \quad e^{-rt} c_z'(x_{z,t}) = &\int_t^{T_\omega} e^{-\delta(t-\theta)}(\mu R_h + \alpha_h)\, d\theta \\ &+ \int_{T_\omega}^{T_\gamma} e^{-\delta(t-\theta)} \omega_\theta \, d\theta + \int_{T_\gamma}^{T} e^{-\delta(t-\theta)}(\mu R_l + \alpha_\ell)\, d\theta \\ &+ \int_T^{\infty} e^{-\delta(t-\theta)} \omega_\theta \, d\theta\end{aligned} \tag{3.18}$$

$$\begin{aligned}&\forall t \in [T_\ell, T_\ell^e], \\ &e^{-rt} c_\ell'(x_{\ell,t}) = \int_t^{T_\omega} e^{-\delta(t-\theta)}(\mu(R_h - R_\ell) + \alpha_h - \alpha_\ell)\, d\theta \\ &+ \int_{T_\omega}^{T_\ell^e} e^{-\delta(t-\theta)}(\omega_\theta - \mu R_\ell - \alpha_\ell)\, d\theta + c_\ell'(0)\, e^{(r+\delta)(t-T_\ell^e)}\end{aligned} \tag{3.19}$$

From (3.19), we get the difference between the optimal MICs during the period of simultaneous investment:

$$\begin{aligned}&\forall t \in [\max_i (T_i),\ T_\ell^e],\ c_z'(x_{z,t}) - c_\ell'(x_{\ell,t}) = \\ &\underbrace{(\mu R_\ell + \alpha_\ell)\, e^{rt} \int_t^{T_\ell^e} e^{-\delta(\theta-t)} d\theta}_{\Delta p} + \underbrace{\left(c_z'(x_{z,T_\ell^e}) - c_\ell'(0)\right) e^{(r+\delta)(t-T_\ell^e)}}_{\Delta c'}\end{aligned} \tag{3.20}$$

14. Appendix C.4 details the phases and the net revenues during those phases (the output price $\omega_t$, the carbon price $\mu_t$, the resource costs $\alpha_{i,t}$).

$\Delta p$ is the discounted value of emissions and fossil fuels that the marginal zero-carbon capacity built at time t allows saving before $T_\ell^e$ when compared to the marginal low-carbon capacity built at time t.
$\Delta c'$ is the difference between the values of the marginal capacities built at $T_\ell^e$ discounted to t. It is strictly positive, as $c_z'(x_{z,T_\ell^e}) > c_z'(0)$ as $c_z'$ is growing by assumption and $c_z'(0) > c_\ell'(0)$ (3.10). □

Indeed, investment costs should be higher for wind power for four reasons: (i) wind saves more GHG than gas; (ii) wind saves fossil energy, compared to gas; (iii) wind has a higher share than gas in the optimal long-term technology mix, and (iv) investment costs are convex.

COROLLARY 3.1. The optimal LCOE of the ZCT and the LCT are different, and not necessarily equal to the electricity price.

*Proof.* Injecting the optimal MICs (3.18,3.19) into the definition of the LCOE (3.17) yields the expected results. □

LCOEs differ from the electricity price because the latter only accounts for variables costs, while LCOEs take investment costs (imperfectly) into account. LCOEs are a "static" representation of marginal costs because they ignore in fact the convexity of the investment cost function and the congestion effects, and therefore fail to anticipate the changes in investment. As a result, depending on the relative speed of change of investment LCOEs of green technologies may differ. The numerical application shows the ZCT has a higher LCOE for the European electricity sector.

### 3.4.2 Ordering investment in carbon-intensive and zero-carbon capital

As a consequence of the intertemporal value of investment in ZCT and LCT, the transition toward a decarbonized electricity sector can take several forms, and in particular:

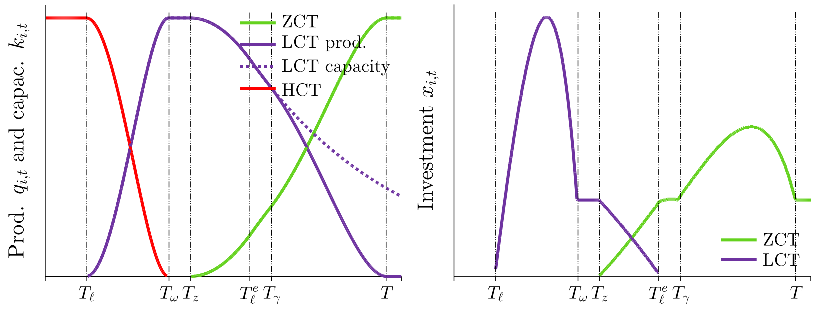
PROPOSITION 3.2. Investment in the ZCT can start before investment in the LCT, even if the latter is less costly.

*Proof.* See C.4 □

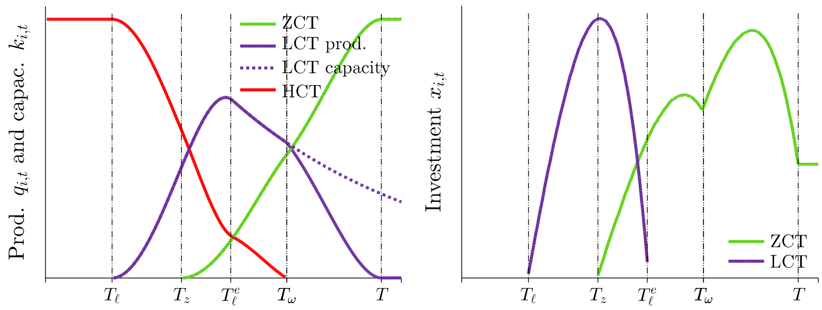
Investment phases may be ordered in following ways:

1. Two successive transitions, starting with LCT investment. The LCT completely replaces the HCT first, then the ZCT replaces the LCT (see illustration in Fig. 3.1a).
2. Two overlapping transitions, with a phase of simultaneous investment in the LCT and the ZCT. Investment in the LCT start first, and investment in the ZCT start before the HCT has been completely replaced (Fig. 3.1b). Investment in the LCT can stop before or after the HCT has been completely replaced.
3. Two overlapping transitions, with a phase of simultaneous investment in the LCT and the ZCT. Investment in the more expensive ZCT start first, and investment in the LCT start before the HCT has been completely replaced. Investment in the LCT can stop before or after the HCT has been completely replaced (Fig. 3.1c).

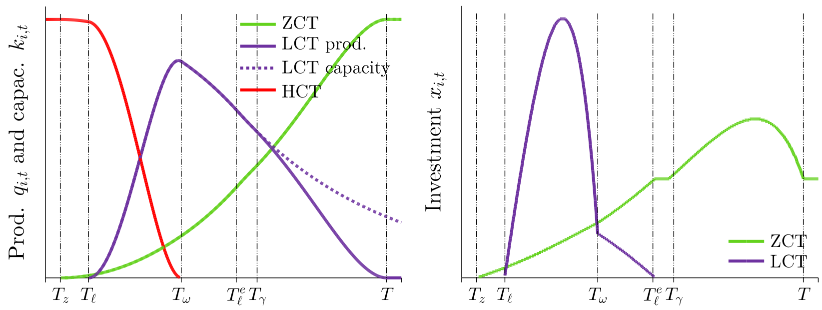
Prop. 3.2 is similar to the finding by Chakravorty et al. (2008) that the optimal extraction of several polluting non-renewable resources may follow several unintuitive orderings. In their work, however, the dynamics comes from the interaction of several scarcity rents; in ours, it comes from the convexity on investment costs.




**(a)** Two successive transitions. HCT is phased out by LCT, then LCT is phased out by ZCT: $T_\ell < T_\omega < T_z < T_\ell^e$




**(b)** Two overlapping transitions, starting with the cheapest substitute (LCT): $T_\ell < T_z < T_\omega < T_\ell^e$




**(c)** Two overlapping transitions, starting with the most expensive substitute (ZCT): $T_z < T_\ell < T_\ell^e < T_\omega$

**Figure 3.1:** Numerical simulations displaying three possible transition profiles. Figures on the left display capacities and productions, figures on the right display optimal marginal investment costs. The parameters used to produce these figures are gathered in C.6.

**Table 3.2:** Technology sets considered in the numerical model

| Set | Acronym | Description | Composition |
|---|---|---|---|
| High carbon technology set | HCT | Average current thermal production mix in 2008 | Gas (approx. 40 % ), coal (approx. 50 % ), oil (approx. 10 % ), source ENERDATA (2013) |
| Low carbon technology set | LCT | Efficient new generation fossil technologies | Efficient gas |
| Zero carbon technology set | ZCT | New generation renewable technologies | Onshore wind, biomass |

The left column of Fig. 3.1 illustrates Prop. 3.1. In particular, Fig. 3.1a displays a case where it is optimal to start with the most expensive option, similarly to the previous result by Vogt-Schilb and Hallegatte (2011).

## 3.5 NUMERICAL APPLICATION: THE CASE OF THE EUROPEAN ELECTRICITY SECTOR

### 3.5.1 Modeling framework, data, calibration

Let us calibrate a modified version of our model with data from the European power sector. In this numerical application, efficient gas power plants (the LCT) and renewable power (the ZCT), e.g. wind, are used to phase out the existing emitting capacities represented as the average current thermal production mix. Table 3.2 gives the technology sets used in the numerical simulation. [15]

To better fit the data, we express installed capacity $k_{i,t}$ in peak capacity (GW), and production $q_{i,t}$ in GWh/yr. Production is constrained by a maximum number of operating hours $H_i$ (lower for wind to capture in part intermittency issues). This constraint captures the imperfect substitution between different green technologies. For instance, a given windmill will produce power only at the moments where it is windy, which expectedly happens a given number of hours per year. [16]

We define the utilization rate $u_{i,t}$ of installed technology $i$ at time $t$ as:

$$u_{i,t} = \frac{q_{i,t}}{H_i\, k_{i,t}} \tag{3.21}$$

We assume for simplicity that all technologies have the same depreciation rates $\delta_i$.

We consider that Europe is price-taker for exhaustible resources (coal and gas), which costs are included in the form of fuel costs $\alpha_i$ (constant in present value).

15. For simplicity and consistency, we will always refer to “gas” and “wind” when speaking of respectively the low-carbon and the zero-carbon technology of the analytical section. The high-carbon existing power plants (the HCT in the analytical section) will be referred to as “legacy”.

16. A better representation of the power generation sector would model windy periods as a stochastic process. This refinement is out of the scope of this paper.

**Table 3.3:** Technology-specific data used in the numerical application.

| | Description | Unit | HCT | LCT | ZCT | Source |
|---|---|---|---|---|---|---|
| $\alpha_i$ | Fuel costs | \$/MWh | 55 | 60 | 0 | OECD (2010) |
| $C_i^m$ | Nominal investment costs | \$/kW | 1 800 | 1 200 | 2 000 | OECD (2010) |
| $X_i$ | Average annual new capacity in Europe | GW/y | 4.2 | 11 | 10 | ENERDATA (2013) |
| $H_i$ | Average annual operating hours | h/y | 7 500 | 7 500 | 2 000 | OECD (2010) |
| $\delta_i$ | Depreciation rate | %/yr | 3.33 | 3.33 | 3.33 | EWEA (2012) |
| $R_i$ | Carbon intensity | $gCO_2$/kWh | 530 | 330 | 0 | ENERDATA (2013), Trotignon and Delbosc (2008) |

The model becomes (omitting the positivity constraints):

$$\min_{x_{i,t},q_{i,t}} \int_0^\infty \sum_i \left(e^{-r\,t} c_i(x_{i,t}) + \alpha_i\, q_{i,t}\right) dt \tag{3.22}$$

$$\begin{aligned} \text{s.t.}\ \ \dot{k}_{i,t} &= x_{i,t} - \delta_i k_{i,t} \\ q_{i,t} &\leqslant H_i \cdot k_{i,t} \\ \sum_i q_{i,t} &= D \\ \dot{m}_t &= \sum_i R_i\, q_{i,t} \\ m_t &\leqslant \bar{M} \end{aligned}$$

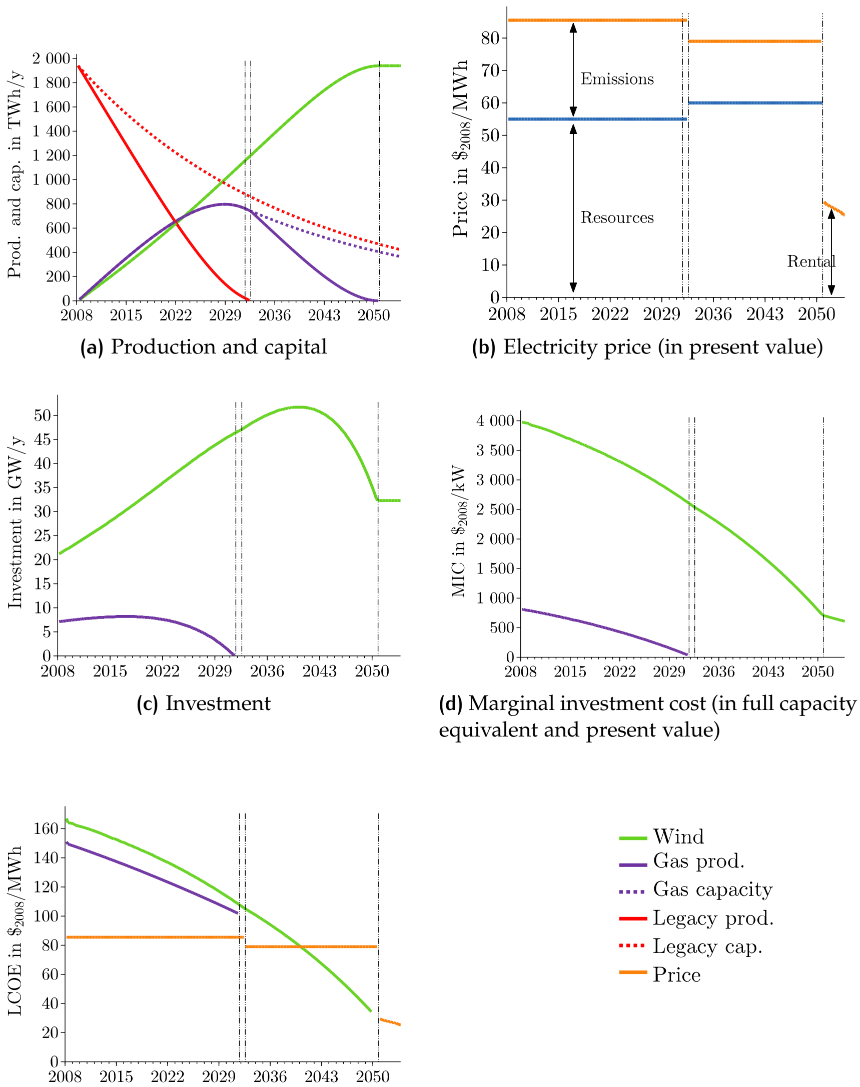
We assume quadratic investment costs. To calibrate the cost functions, we assume that when investment equals the average annual investment flow in Europe between 2009 and 2011 ($X_i$), the marginal investment cost $C_i^m$ is equal to the OECD median value for 2010 (as found in OECD (2010)). We write the cost function as:

$$c_i(x_{i,t}) = C_i^m \cdot X_i \cdot \left( A\, \frac{x_{i,t}}{X_i} + \frac{1-A}{2} \left(\frac{x_{i,t}}{X_i}\right)^2 \right) \tag{3.23}$$

$$t = 0 \implies c_i'(X_i) = C_i^m \tag{3.24}$$

$A$ is a convexity parameter, assumed equal across technologies. If $A = 1$, the marginal investment cost is constant (the cost of new capacity does not depend on the investment pace), and optimal investment pathways would exhibit jumps: there would be no congestion in investment (Vogt-Schilb et al. 2012). If $A = 0$ the marginal cost curves starts at zero (the cost of new capacity doubles when the investment pace doubles) and capacity accumulated at very low speed is almost free ($\lim_{x_{i,t}\to 0; A=0} c_i'(x_{i,t}) = 0$). An intermediate value $A \in (0,1)$ means that new capacity is always costly, and that its cost grows with the investment pace.

Fig. 3.2a to Fig. 3.2e are obtained with $A = 0.1$, i.e. with a relatively low convexity (investment cost doubles at 1.9 times the nominal pace). For instance, in the base year (2008), building one Watt of new wind capacity at the pace of 10 GW/yr costs 2\$/W. At 20 GW/yr, it would cost 3.8\$/W.




**(a)** Production and capital

**(b)** Electricity price (in present value)

**(c)** Investment

**(d)** Marginal investment cost (in full capacity equivalent and present value)

**(e)** Levelized cost of electricity (present value)

**Figure 3.2:** Outputs from the numerical application to the European electricity sector

**Table 3.4:** General parameter values used in the numerical application.

| | Description | Unit | Value | Source |
|---|---|---|---|---|
| $r$ | Discount rate | %/y | 5 | |
| $\bar{M}$ | Carbon budget | $GtCO_2$ | 17 | EU (2011), Trotignon and Delbosc (2008) |
| $D$ | Power demand | TWh/y | 1 940 | ENERDATA (2013) |
| $A$ | Convexity parameter | · | 0.1 | |

Fig. 3.3a and Fig. 3.3b are obtained respectively with $A = 0.2$ and $A = 0.001$ (i.e. investment cost doubles at respectively 1.8 and 1.999 times the nominal pace).

The emission allowances allocated to the power sector amounted to $E_{ref} = 1.03\ GtCO_2/yr$ in 2008 (Trotignon and Delbosc 2008). The reference fossil energy production (from coal, oil and gas) was $D = 1\,940$ TWh/yr that year (ENERDATA 2013), leading to a reference emission rate of 530 $tCO_2$/GWh. We take a carbon budget corresponding to roughly half of the BAU cumulative emissions, i.e. 17 $GtCO_2$.

We calibrate the depreciation rate as $\delta_i = 1/\text{lifetime}$ and assume a lifetime of 30 years for all technologies (OECD 2010). We use $r = 5$ %/yr for the social discount rate.

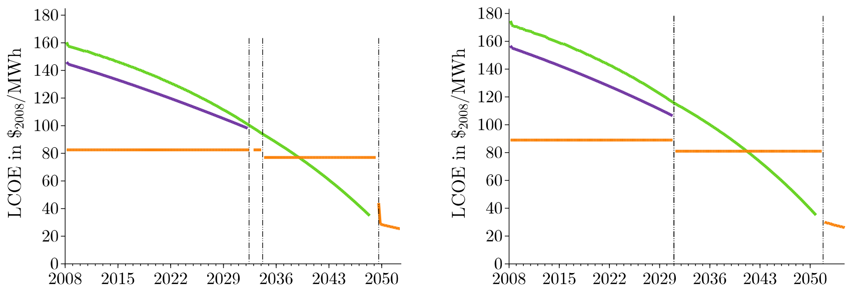
### 3.5.2 Results

Fig. 3.2 shows various variables of the numerical application to the European electricity sector. Despite lower fuel costs, the social planner does not invest in the legacy capacity, which is entirely phased out in 2035 (Fig. 3.2a). There is unused gas capacity as soon as the dirty technology is phased out ($T_\gamma = T_\omega = 2035$), and investment in gas stops a couple of years earlier ($T_\ell^e = 2033$).

Investment in both efficient gas and wind power starts from the beginning of the simulation (Fig. 3.2c). Until 2038, investment in wind capacity grows over time. Investment starts at 18 GW/yr in 2008, almost twice the actual average investment rate $X_i$, and reach 60 GW/yr in 2038. It decreases after 2040 as most of the power plants have already been replaced (Fig. 3.2a), and stay constant after 2045 to maintain the wind capacity constant.

Fig. 3.2d displays the resulting marginal costs for new capacity (MICs) along the period, expressed in present value. They decrease over time, as the average power plants becomes less and less carbon-intensive, making investment in low carbon capacity less and less profitable. Investment in gas remains relatively low by contrast. Prop. 3.1 holds: the MIC is always higher for wind.

Electricity prices are displayed in Fig. 3.2b. When production comes from fossil resources the price decomposes as resource cost and emission cost (Lemma C.1 and Lemma C.2). In a first phase (before 2035), the marginal capacity is the legacy dirty technology, and the electricity price is high. After the dirty technology has been phased out, from 2035 to 2045, gas becomes the marginal technology and the price drops. The endogenous carbon price is 46 $/$tCO_2$, a figure compatible with the projections from IEA (2012), and the lower carbon intensity of gas compared to coal more than compensates the higher resource cost. In the last phase, all the electricity




(a) $A = \frac{1}{5}$

(b) $A = \frac{1}{1000}$

**Figure 3.3:** Levelized cost of electricity (present value) for two values of the convexity parameter

comes from wind, and electricity price equals the rental cost of wind power plants (Lemma C.3).

#### 3.5.2.1 *Optimal levelized costs*

Fig. 3.2e shows the levelized costs of electricity along the optimal pathway simulated for the European Union, and compare them with the corresponding electricity price. The optimal LCOEs are found higher than electricity prices, because the latter is equal to the variable costs of the marginal technology, it does not represent investment costs.

LCOEs account for GHG emissions and variable energy costs, but assume investment costs are constant. Because investment costs are convex, investing early reduces the discounted cost of the transition, and the optimal long-term technology mix has consequences on optimal short-term efforts. Here, wind capacities are built faster, and their investment drops also faster than gas. As a result, using LCOE to assess wind investment is a greater approximation than for gas, and its LCOE is higher.

Vogt-Schilb et al. (2013) demonstrate that a similar criteria (the levelized abatement cost) is accurate only if capacity costs are constant in time and do not depend on the investment pace. In our numerical simulations, the capacity cost slowly increases with the investment pace (the marginal investment costs increases by a factor 1.9 when the investment pace doubles compared to the nominal pace), and the optimal levelized cost of electricity produced from wind is greater than the levelized cost of electricity produced from gas. This suggests that LCOEs should not be used as a rule-of-thumb metrics to assess investment.[17]

Fig. 3.2a show that the difference in the LCOEs of wind and gas depends on the convexity of the investment cost functions (for higher values of the convexity parameter ($A \to 1$), the investment cost function becomes linear). We find, as shown in Fig. 3.2a, that in the European electricity sector, the lower the value of $A$, i.e. the higher the convexity of the investment cost function, and the greater the difference between the LCOEs. The structure of the model forbids to find an equilibrium for $A = 1$ or $0$, but we expect equal LCOEs in a model without congestion (as in the static version of Appendix C.3).[18]

17. Further research should carry out a sensitivity analysis on the convexity parameter $A$ and the climate policy stringency $\bar{M}$.

18. This effect shall be thoroughly studied in a future sensitivity analysis.

In our simulation, if decision makers decided investment in new capacity for the European electricity market by comparing LCOEs to the electricity price, they would build too much low-carbon capacity (e.g. gas), and not enough zero-carbon capacity (e.g. wind).

## 3.6 CONCLUSION

We investigate in an analytical model the optimal timing of investment in low-carbon (e.g. gas power plant) and zero-carbon (e.g. renewable power) capital to phase out preexisting high-carbon capital (e.g. coal power plants) in the electricity sector, facing an inelastic demand and a carbon budget. We assess this investment using various representations of marginal costs:

- the marginal investment cost (MIC),
- the levelized cost of electricity (LCOE), or discounted costs over discounted production, taking the cost of emissions and resources into account, and
- the marginal implicit rental cost of capital (MIRCC), or efficient market rental price of capacities, taking endogenously the congestion costs into account.

We then run a numerical simulation calibrated on the European power sector and compute the optimal transition trajectories.

We find that the dynamic features of marginal costs are essential in assessing the cost-efficiency of investment in low-carbon capital.An incomplete representation of the congestion effects in investment leads to a sub-optimal transition, because the variations in investment costs due to the increasing or decreasing amounts of investment needed are ignored.

We discuss the use of "static" representation of long-term marginal costs: MICs and LCOEs. We show analytically that MICs (represented in full capacity equivalent) should always be higher for completely carbon-free technologies such as wind than for low-carbon technologies such as gas. This is not explained only by cheaper operation costs of renewable power coming from both the carbon price and nil fossil energy requirements. Renewable power may be used forever, while the exhaustible and polluting low-carbon capacity built to phase out the preexisting dirtier plants will eventually be phased out itself by the renewable power. As a result, on the optimal trajectory, gas capacities may be under-used.

We find also that contrary to what textbooks say, LCOE should not be equal between technologies, even when they account for emission and resource costs, because they do not take congestion effects into account. In the numerical application to the European electricity sector, we find that the LCOE of wind is always higher than the LCOE of gas.

LCOEs account for GHG emissions and variable energy costs, but assume investment costs are constant. Because investment costs are convex, investing early reduces the discounted cost of the transition, and the optimal long-term technology mix has consequences on optimal short-term efforts. Here, wind capacities are built faster, and their investment drops also faster than gas. As a result, using LCOE to assess wind investment is a greater approximation than for gas, and its LCOE is higher.

This suggests that in the European electricity sector, ranking technologies according to their LCOE would result in too much investment in intermediate technologies (such as gas), and too little in more expensive zero-carbon capital (such as renewable power). The LCOE does not provide enough information to assess and rank investment in polluting fossil-fueled and zero-carbon capital.

Another finding is that the ordering of investment does not follow any easily predetermined order: investment in the expensive carbon-free capital (renewable power) may begin at the same time, or even before, investment in the lower-cost low-carbon capital (e.g gas plants).

On a more methodological note, our results suggest that congestion cost play an essential role in assessing investment trajectories, and that the speed of investment should explicitly be part of the modeling choices. While numerical model of the electricity sector (such as MARKAL or TIMES, Fishbone and Abilock (1981), Loulou (2008), Seebregts et al. (2002)) embed an implicit version of these constraints in the form of maximum investment speeds, to our knowledge no model does it explicitly.

Several extensions would be of interest. Decentralizing rigorously the equilibriums, for instance by incorporating a real convex demand or utility function, would yield interesting policy implications, and would allow further testing the influence of convexity in investment costs by defining a BAU equilibrium without congestion effects. Representing more "realistic" features of electricity markets such as some uncertainty on the future demand, some degree of imperfection in the competition or the anticipations of agents, would also allow more accurate and relevant insights on policy implications.

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# 4 ASSESSING FRENCH CLIMATE POLICY IN THE ELECTRICITY SECTOR: TOO MANY INSTRUMENTS? [1]

## 4.1 INTRODUCTION

The French climate and energy policy is undergoing a process of consultation and debates, and faces both important challenges and opportunities. A nation-wide debate on the energy transition just ended in September 2013, intended to define the future mix of instruments to reach ambitious long term climate policy objectives, in a context of increased political and economic uncertainty. It opened a new window of opportunity to set a *contribution climat-énergie* aiming at pricing the carbon content of energy consumption. In a context of low carbon price, this instrument would be the cornerstone to achieve France's ultimate objective to reduce by 75 % its emissions by 2050 (the *facteur 4*), and thus going beyond its Kyoto commitments. Many other policy instruments affecting fossil emissions already exist however, and are expected to be carried through, raising questions over possible negative interactions and unnecessary additional costs.

One of the main challenges of the French climate and energy policy is to successfully reform this instrument mix, and possibly simplify it. The French climate and energy policy is the result of three different policy developments, having only little in common:

- the various attempts to price the carbon content of energy, in parallel to the European initiative to implement an emission allowance market;
- the expansion of renewable energy power (REP) promotion;
- the long history of incentives and regulations to reduce the consumption of energy in buildings.

The last two resulted in the implementation of several policy instruments, having different characteristics, various impacts on the electricity sector and potential negative interactions with each other. The purpose of this chapter is to give a qualitative assessment of the cost-efficiency of this policy instrument mix by considering its effect in the electricity sector, and to sketch answers regarding possible simplifications of the mix.

It will do so by asking five questions spanning this whole thesis:

1. Does the carbon price signal triggers enough greenhouse gases (GHG) emission reductions in France to reach its ambitious target of reducing emissions by a factor 4 in 2050?
2. In case of failures of this carbon price signal, do additional instruments help overcome them?
3. Do those additional instruments interact with each other, and does it affect the efficiency of the policy mix as a whole to reach its long term emission reduction target?

1. Parts of Sections 4.2 and 4.3 are published in (CECILIA2050 2013), and Sections 4.2.1 and 4.3.1.1 appear in (Branger et al. 2013).

4. Is this policy mix efficient enough to reach this target?
5. Can the mix be made more effective by simplifying it and removing or reforming some instruments?

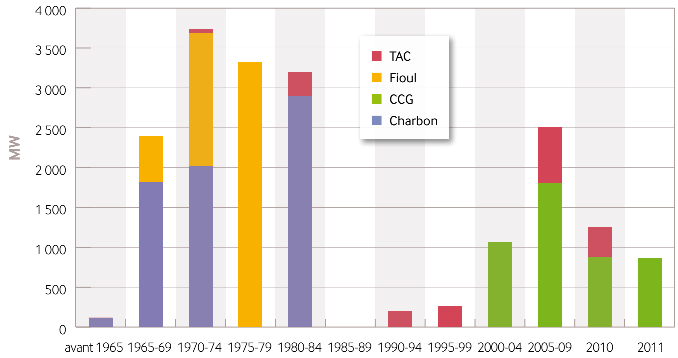
This chapter will focus on the efficiency of the current climate and energy policy mix in the electricity sector, whether on the supply or the demand side. As in the other member states of the European Union (EU), the French climate and energy strategy is stretched over all the sectors of the economy, and ranges from mitigation to adaptation. The electricity sector is however thought to bear a substantial part of the mitigation burden, because (i) it is a major carbon-intensive industry not subject to international competition (and is therefore not at risk of carbon leakage at the European level, see e.g. (Hourcade et al. 2007)), (ii) through electrification of the transport sector, increased use of heat pumps for heating and the enabling of large electricity-intensive CCS installations, it may help decarbonize other sectors of the economy, (iii) it already disposes of several mature mitigation options. Recent prospective scenarios featuring a minimum of 75 % emission reductions in 2050 plan to almost completely decarbonize the electricity sector by then (see e.g. scenarios by Eurelectric (2011), EU (2011b), IEA (2012)).

The electricity sector already faces more stringent climate regulations than other carbon-intensive sectors in Europe. It does not face the same risks of competitiveness losses than many other carbon-intensive sectors (such as cement, steel, aluminum, pulp and paper, etc) facing at various degrees high carbon costs in production or higher exposition to international competition (Meunier et al. 2012). The concentrated nature of electricity production makes it easy to monitor and enforce regulations: even if the transportation sector is similar to the electricity sector in that its output (transportation) cannot be exported, regulating emissions from private transportation is much more difficult because of the number of emitters; instead regulations focuses on performance standards enforced at the construction or the retail level.[2] As a result, electricity production accounted for half of the allocations in the second phase of the European Union Emission Trading System (EU-ETS), and electricity is the only sector where allocations were lower than emissions (Trotignon and Delbosc 2008).

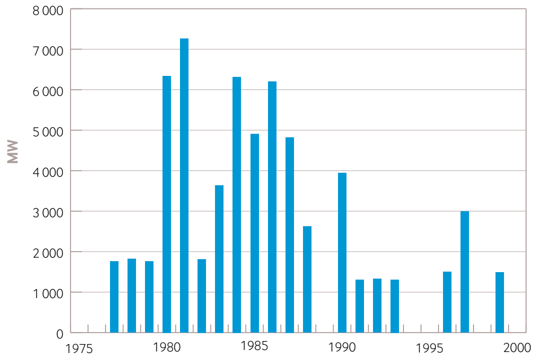
The electricity sector holds moreover several key assets and opportunities. Several technologies already exist that can produce massively carbon-free electricity, or reduce substantially the need for emitting power. The timing of the transition coincides in France with the natural replacement of large volumes of fossil and possibly nuclear capacity.[3] Figure 4.1 represents the connection date of the French centralized production capacity. The first generation of most polluting coal and heavy fuel oil capacity will reach 45 to 50 years, and the oldest nuclear plants are now 35 years old. The regulatory status of existing capacities is also about to change, with most of the very polluting capacities complied to shut down by the end of 2015. This

2. Market-based instruments are starting to be implemented in France and Europe, such as the *Bonus-malus* penalty system and efficiency certificates, but all these instruments are still enforced at the production and retail level.

3. Nuclear technologies have a variable share in the production mix in the transition scenarios, ranging from *status quo* (Acket and Bacher 2012, UFE 2011) to complete phase-out (Dessus 2012, négaWatt 2011). This chapter focuses on qualitative aspects of a transition toward a decarbonized electricity sector. Nuclear can be part of the zero-carbon technology set, or the transition can be considered a phasing-out from carbon-intensive technologies and nuclear, in which case the problem is many magnitudes more difficult, and support policies would have to be adapted accordingly. The French président de la république announced a partial phase-out from nuclear, with a decrease to a 50 % share of nuclear in the French production mix in the coming decades.




(a) Fossil technologies.




(b) Nuclear capacity.

**Figure 4.1**: Connection date of the French centralized capacity. Source: RTE (2012).

provides a window of opportunity to make use of the natural replacement of large shares of generation capacities to start the transition process toward a completely decarbonized electricity sector and toward an economy less dependent on energy imports thanks to a reduced energy consumption.

To fully acknowledge the political constraints and the path-dependency of the French climate and energy policy, Section 4.2 sketches its history and presents the main instruments affecting fossil emissions in the electricity sector, grouped by main objective. Section 4.3 reviews the literature on the efficiency of individual instruments and gives a preliminary assessment of the carbon price signal in France, of the efficiency of the individual instruments in the French climate and energy policy mix and of their potential negative interactions. Section 4.4 lists the main economic rationales for such combinations, and discusses whether they actually correct potential failures of the carbon price signal. Section 4.5 concludes and discusses some recommendations for simplifying or reforming the instrument mix.

## 4.2 FRENCH INSTRUMENTS ARE NOT THE RESULT OF A HARMONIZED APPROACH

Although the main long term objective of climate policy is to curb GHG emissions and to fight against damages from climate change, the climate and energy policy is scattered across several sector-specific targets and instruments. In France, the long term targets for climate policy are set by the energy policy strategy law (loi POPE, see Sénat (2005)), targeting a 75 %

overall reduction of GHG emissions by 2050. An intermediary target also exist at the European level: a 20 % GHG emissions reduction target by 2020 compared to 2005 has been transcribed into French law to comply with the European Climate Framework (EU 2010, MEDDAD 2007).

However, no single instrument has been setup to achieve this overall objective. Instead, several sector-specific targets co-exist. While the EU-ETS caps the emissions of installations above a certain size in the most energy-intensive sectors (EU 2009a), France declared 14 % emission reduction target for all sectors not covered by the EU-ETS by 2020 compared to 2005. The indicative European target of 20 % energy consumption reduction by 2020 (compared to projected BAU consumption in that year) in all sectors (EU 2008; 2011a) has been transcribed in the French National Action Plan for energy efficiency into multiple targets aimed primarily at the transportation, building and residential sectors (MEDDTL 2011). The *Grenelle 2* law (CDDAT 2010) declares a 38 % energy consumption reduction target for existing buildings until 2020. Finally, France has a binding target of increasing the share of renewable energy up to 23 % of total energy consumption by 2020 (MEEDDEM 2009), with specific targets for the electricity and transportation sectors.[4]

This section presents the main French policy instruments affecting the electricity sector, grouped according to the main specific objectives of the French climate policy. It briefly presents the history of each policy instrument group, and gives elements on the various trade-offs faced by policy-makers when implementing them. Table 4.1 lists these instruments grouped by target.

### 4.2.1 Carbon pricing and emission reduction instruments

The EU-ETS was explicitly set up to reduce emissions by efficiently allocating abatement efforts across sectors, technologies and mitigation options. It is also meant to serve as a signal for investors and policy makers by setting a price on emissions, and thereby plays a special role as a driver for investment and as a tool for increased perception of climate policy in business decision-making (Hourcade et al. 1993). Although dispositions are currently being made to remove some allowances in response, among other effects, to increased carbon-free REP generation, the EU-ETS was set up as a flagship instrument, and was not designed to minimize interactions with other climate and energy instruments or to adapt to external parameters.

#### 4.2.1.1 *A brief history of the European Union Emission Trading System*

The EU-ETS was born out of two failures (Convery 2009). The first was the impossibility of setting a carbon and energy tax in the EU at the beginning of the 1990's, due among other reasons to the unanimity rule for fiscal decisions in the European Community. This raised the need for an alternative policy. The second failure occurred during the negotiation of the Kyoto Protocol in 1997. To get the agreement of the United States and their allies, the European institutions finally accepted flexibility mechanisms they once strongly opposed.

The following year they proposed to implement an ETS within the European Union. Five years later, the 2003/87/EC directive gave birth to the EU-ETS (EU 2003), a scheme divided into two distinct periods: a learning

4. See following sections for details on the scope of individual instruments. See also Section 4.4 for a discussion on the rationales for multiple objectives and instruments.

**Table 4.1:** List of the French climate and energy policy instruments detailed in the chapter, classified by main target

| Policy instruments | Carbon pricing and emission reduction | Energy efficiency and energy consumption | Promotion of renewable sources of energy |
|---|---|---|---|
| EU-ETS | √ | | |
| Carbon tax | √ | | |
| Energy efficiency certificates | | √ | |
| Building code regulations | | √ | |
| Tax credits and preferential loans for energy efficiency investment | | √ | |
| Feed-in tariffs | | | √ |
| Renewables tenders | | | √ |

phase (2005-2007) and a second phase corresponding to the commitment period of the Kyoto protocol (2008-2012). A major reform in 2008-2009 (EU 2009a) added a third phase for the period 2013-2020.

Largely superior to forecasts between May 2005 and April 2006, the Phase 1 European emission allowances (EUA) price collapsed when it became clear that emissions were going to be inferior to analysts' forecasts and to the global number of allowances in the market in 2005 and 2006. This excess of allowances comes from three sources. First, the EU-ETS induced around 2 % to 5 % emission reductions, a decrease of same magnitude as the allowances surplus. Second, public authorities in charge of the allocation plans (the member states and the European Commission) had only little information on the emissions of covered installations, before any large-scale and efficient monitoring mechanism was put in place. Finally, the will of certain member states to protect their home industries may have worsened the situation (Convery and Redmond 2007). While some member states like the United Kingdom played by the rules and distributed less allowances than expected emissions, others were extremely generous. In France, allocations largely exceeded emissions each year (see Figure 4.2). This is a unique case in the biggest member states and suggests a massive overallocation. [5]

During the second phase (2008-2012), the cap was more binding from the beginning (10 % inferior to the first phase). The Commission had more information this time, as it knew the actual emissions of 2005 during the assessment of national allocation plans, and was able to restrain the generosity of the member states. During the second phase, the carbon price remained high until summer 2008, and then fell steadily to reach 3 €/t$CO_2$ in 2013 (see Figure 4.7), mainly because the demand for emission allowances sharply dropped after the economic crisis.

The EU-ETS was substantially modified toward more centralized and harmonized allocation rules and emission reduction targets for the third phase (2012-2020). More gases and sectors were included, and part of the allowances are issued through auctions. The implementation of this phase

5. The estimation of a 15 % overallocation for France in Phase 1 was forecast independently by the economist Olivier Godard (2005) and the NGO Climate Action Network http://www.rac-f.org/3eme-version-du-PNAQ-Un-pas-en after the disclosure of the first national allocation plan.

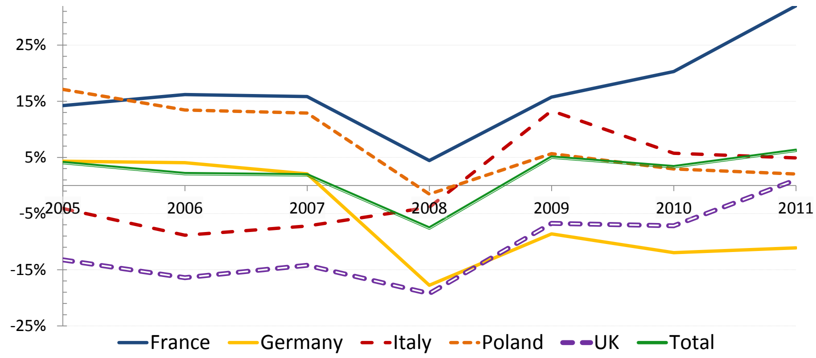



**Figure 4.2:** Surplus (+) or deficit (−) of allowances for the biggest member states and for all countries of the EU-ETS, in percentage of emissions. Source: own calculations based on Sandbag (2013)

is concomitant to the negotiation for an Energy Efficiency Directive and a framework for extended climate and energy objectives for 2030. Despite this, and the fact that allocations gradually decrease in the third phase, the carbon price remains close to its 2013 low. Dispositions are currently being made to remove temporarily (*backloading*) some allowances and increase the carbon price, but no real adaptation mechanism has been built into the EU-ETS to respond to changes in the level of economic activity or the structure of the electricity generation mix for instance.

#### 4.2.1.2 *The successive attempts to set up a carbon tax in France*

Aiming at giving a price incentive to reduce carbon emissions, the carbon tax has been proposed and rejected several times in France on the ground of equity issues. In 2000, the *Constitutional Council* (the court which checks the compatibility of new laws with the Constitution) rejected a proposal which would have taxed CO2 emissions and energy consumption by firms. It argued that this tax infringed the principle of equal taxation, because large emitters would have benefited from substantial rebates. After a promise made during the elections, the French president Nicolas Sarkozy proposed in 2009 a *Contribution climat-énergie*, where emitters (both households and firms) were to be taxed. Revenues raised from households would have been distributed back as lump-sum transfers to households, while revenues raised from firms would have been used to reduce pre-existing taxes. Emitters already covered by the EU-ETS were to be exempted. Due to this exemption, and others (such as emission from farmers), the Constitutional Council censored again the carbon tax.

The Constitutional Council never opposed the principle of the tax, but only the rebates given mostly to some energy-intensive industries. Following the recent public debt crisis and the *national debate on energy transition*, the present left-wing government announced a new carbon tax project to be set up in 2015 (with a trial period in 2014, where other taxes will be decreased by the same amount for fuels). This new project is expected to be close to the previous one, detailed in great length in the 2009 project finance law for 2010 (Combet 2013).[6] The objective is to mitigate emissions from sources not already covered by similar mechanisms, such as the EU-ETS. Various exemptions have to be expected, to protect fragile industries

6. The new project will probably be substantially changed before it is active, but the last proposals were around €7/t$CO_2$ in 2014, €14.5/t$CO_2$ in 2015 and €22/t$CO_2$ in 2016.

and powerful lobbies, as has been observed in the previous attempts (high emitters with high exposure to international competition, or agriculture for instance).

The level of this future tax is most uncertain. A 2009 stakeholder and expert group led by the *Conseil d'analyse stratégique* (a public body in charge of expertise and stakeholder dialog) set the optimal level of the carbon tax (the social cost of carbon) at €32/t$CO_2$ in 2010, and rising to €100/t$CO_2$ in 2030 and €200/t$CO_2$ in 2050 (Quinet et al. 2009). The expected abatement among the covered sectors was 7.5 % after a few years and 14 % in 2020 (Ademe 2009). After political compromises, the French president set the initial level of the projected tax at €17/t$CO_2$ in 2009. By equalizing the marginal costs of the various abatement options across almost all sectors , the carbon tax allows maximum cost effectiveness. To this extent, exempting actors already covered by another equivalent scheme (e.g. the EU-ETS) makes sense, lest imposing a double burden on those actors, but exempting other actors would reduce the global effectiveness of the instrument, leaving untapped potential savings.

### 4.2.2 REP promotion instruments

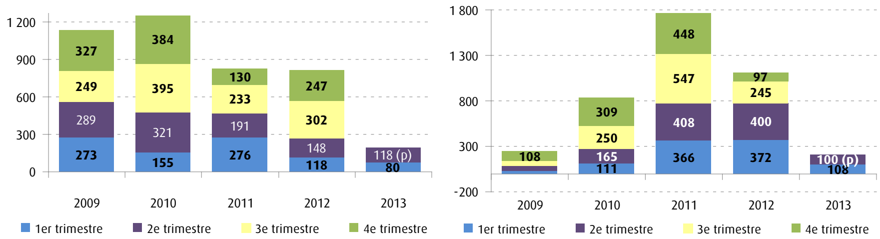
While complying with the Kyoto protocol remains the primary objective for REP policies at the European level and other rationales are often used by member states, in France REP promotion instruments mainly aim at increasing the share of renewable sources in electricity production. Under the provisions of Directive 2009/28/EU (EU 2009b), by 2020 23 % of France's final energy consumption must be generated from RES. The French government also targets a share of 27 % REP by 2020 in the electricity sector.

In France, REP are promoted by two main instruments. Feed-in tariffs (FiTs) promote small-scale renewable generation capacities for all technologies, while tenders promote large-scale renewable generation capacities (mainly offshore wind and large-scale solar). Other instruments exist (MEEDDEM (2009) lists 37 measures, among which instruments having another main target, e.g. consumption reduction), but their financial impact is smaller, and they are less likely to interact with the other instruments discussed in this chapter. Some instruments detailed in Section 4.2.3 promote fossil fuel consumption reductions by using renewable sources (mainly biomass) on the demand-side, but the bulk of REP expansion comes from the supply-side incentives of feed-in tariffs (FiTs) and tenders, and are thus largely independent from energy efficiency (EE) incentives.

#### 4.2.2.1 *A brief history*

Since its creation, the historical French production monopoly has a regulatory obligation to purchase electricity from installations smaller than 8 MW at rates negotiated on an individual basis, but there was no official REP target.[7] Despite early R&D and demonstration efforts in the fifties and seventies, the story of wind deployment in France starts in 1994, when the Minister for Environment Michel Barnier starts a national debate on energy. In 1996 a tendering scheme was chosen over FiTs inspired by the British Non-

7. The electricity sector nationalization law of 1947 allowed the existence of small independent producers by obliging the incumbent to purchase the electricity produced, although at negotiated fare. Hundreds of small hydroelectric producers and dozens of municipal distribution companies, representing around 5 % of consumers, eluded nationalization and still benefit from this scheme.




(a) Wind (b) Solar

**Figure 4.3:** New wind an solar capacity in France per quarter (2009-2013) in MW. Source: CGDD (2013).

Fossil Fuel Obligation. The program "Eole 2005" was launched, with a target of having 500 MW of installed capacity by 2005.

The program never achieved its ambitions and stopped brutally in 2001, replaced by FiTs in application of the Directive 96/92/EC on the liberalization of the electricity markets. The purchase obligation was restricted to renewable energy, and extended to installations up to 12 MW. The tariffs were aligned on the German rates, but no clear target was defined.

When the grid connection demands unexpectedly exploded (up to several GW), the lack of preparation and lengthy connection procedure led to a complete congestion of REP projects. Targets were finally set in the 2003 Multi-Annual Investment Program (2 to 6 GW by 2007, including .5 to 1.5 off-shore). The same year, official instructions were issued to accelerate the connection procedures by local officials, who used to add delays by fear of local opposition. An indicative target was also set by the 2003 renewable electricity Directive, to reach a 21 % share of renewable electricity production 2010. This target has never been reached.

In 2004, the French government started again inviting tenders for large-scale renewable projects. 12 calls were made between 2004 and 2013, mostly for wind energy, but no *ex-post* assessment is available. The last tenders targeted photovoltaics (PV) projects above 100 kW, and several major offshore wind power projects, for a total of 3 GW to be installed between 2012 and 2020 on 5 sites. There are plans for other calls to reach an additional 6 GW offshore wind capacity in 2020.

New targets were set in the 2009 Multi-Annual Investment Program, following the 2008 national debates on environmental policy (the Grenelle de l'environnement, which gathered representatives from the civil society). These new targets now count as the official 2020 targets for France: a share of 23 % of renewables in final energy consumption by 2020 and a share of 27 % of final electricity consumption.

After an increase between 2003 and 2009, the FiTs were substantially modified and reduced in 2009, to take into account decreasing production costs of fast evolving technologies such as solar PV. In 2011 another major change was introduced to let PV tariffs decrease on a quarterly basis, allegedly to improve the responsiveness of the policy to technical changes and cost reductions. It also defined an overall annual cap, above which all further installations are subject to a lower tariff. These changes were made in response to the boom in installed solar capacity (+3 GW since 2011, 2.4 GW still waiting to be connected to the grid).

The FiTs and the grid connection charges are financed through an earmarked tax on electricity consumption (the social contribution to electricity consumption (CSPE)), which also substantially increased in the last years (from €7.5 /MWh in 2011 to €10.5 /MWh in 2012 and €13.5 /MWh in 2013), but slower than the financing needs (CRE 2013). The total charges represented 5.2 bn€in 2012, 52 % of which are used to finance the FiTs. They are however still insufficient, a CSPE of €18.8 per MWh electricity produced would be necessary to cover those charges (CRE 2013).

While some obligations remain, such as the obligation to make an impact assessment and have financial guarantees for the dismantling, some administrative were removed. In January 2013 the "Brottes law" abolished the obligation to install at least 5 mills and the restriction to build into special development zones, but connection procedures are still particularly lengthy and tedious compared to other countries. In particular, for solar projects bigger than 4.5 MW, a special exploitation permit has to be issued, and projects bigger than 250 kW need a special certification to benefit from the FiTs. Then investors have to apply to the transmission grid operator for a connection, with further delays. As a consequence, the amount of new wind capacity has decreased from more than 1 to 1.2 GW new capacity in 2009 and 2010 to approx. 800 MW in 2011 and 750 MW in 2012, and even less in 2013 (see Figure 4.3). The outlook is even worse for solar, whose new capacity peaked in 2011 with almost 1.8 GW new capacity and dropped by more than 75 % in the first quarter of 2013 compared to 2012 and 2011. The 23 % target for REP are out of reach with such growth rates.

### 4.2.3 Main EE promotion instruments

Energy efficiency and savings policy instruments primarily aim at reducing primary energy consumption. Social objectives (linking to energy poverty or simply the price of electricity) seem however to have played an important role, as the results of these policies are more clearly visible by all citizens on their energy bills.

The main target, promoted by the EU (EU 2008; 2011a) and set by the National Plan for Energy Efficiency (MEDDTL 2011), aims at reducing the total final energy consumption by 20 % in 2020. It has been split into a variety of sectoral targets, among which the retrofitting of 38 % of the existing building stock by 2020 and a 2 % to 2.5 % annual reduction in energy intensity.
The French EE instrument mix consists of four main elements:

1. the energy efficiency certificates (EEC) scheme,
2. building codes,
3. the sustainable Development Tax Credit,
4. the zero-rated eco-loan.

#### 4.2.3.1 *A brief history*

Until energy conservation attracted renewed attention with the emergence of climate change issues, the French implication in EE measures followed the oscillations of the oil price (Leray and de la Roncière 2002, Martin et al. 1998). France started implementing EE policies after the first oil shock in 1973, from early construction standards to governmental agencies in charge of information and education. In the eighties and the nineties, the decreasing oil price diverted the attention of policy makers and the ambition of EE policy lessened.

EE is now one of the most uncontested means of action against both the increasing cost of energy imports and climate change (Levine et al. 2007). A national debate, the Grenelle de l'environnement, gathered representatives of civil society and set ambitious targets to reduce energy consumption and energy intensity, and paved the way for a complete policy mix.

This set of new and refitted instruments consists of comprehensive performance standards, along with voluntary instruments such as tax rebates or preferential loans for individuals giving incentives to invest beyond this standard, and a flexible obligation scheme for energy retailers (Giraudet et al. 2012b). The setting of standards and the construction of new buildings have been shown to be a main driver of the reductions in energy consumption for heating since the first oil shock (Martin et al. 1998).

The new building codes (thermal regulation (RT) 2012) are ambitious compared to other countries (around 50 kWh/m²/yr.) and an even more ambitious legislation is planned for 2020. On the contrary, thermal regulation for renovation is rather lax, and individual voluntary measures (preferential loans, tax rebates) have been set up to incentivize investment. Those instruments have been widely used (Insee 2010, SGFGAS 2012), but they do not necessarily reflect the marginal cost of consumption reduction (Mauroux 2012), despite standardization of actions and frequent changes in the eligible technology list. Moreover, they subsidize shallow renovations which are not compatible with the ambitious policy targets (-38 % in energy consumption from buildings in 2020, -75 % in GHG emissions overall in 2050).

#### 4.2.3.2 *The energy efficiency certificates scheme*

The EEC is composed of an obligation to achieve a given target of energy consumption reductions, backed by a market to exchange the certificates and a penalty for non-compliance. For the end of the current compliance period, energy retailers (electricity, heating fuel, gasoline) have to provide a total of 345 bn certificates, or 345 TWh cumulated and discounted over the lifetime of all the investment made. To produce certificates, obligated parties can invest in a set of standard actions in households, industry (except in installations covered by the EU-ETS to avoid double counting) or in the service sector (such as insulation, boiler replacement, motor replacement in some industries, energy management systems, etc.).

This instrument is subject to large indirect costs to participants. Among other costs, they have to develop an organization to find potential savings among their customers and invest in targeted advertising. Those indirect costs are not subsidized (Giraudet et al. 2012a). Except those costs, the economic efficiency of the scheme is high; it incentivizes the use of the cheap potentials first. It is more efficient than a pure subsidy (Quirion and Giraudet 2008) in that it reduces the rebound effect if the cost of the system is passed on to consumers, which is not clearly the case in electricity and gas, for which the retail price is regulated.

#### 4.2.3.3 *Building code regulations*

The building code regulations set standards for the energy consumption of new buildings. The first one (the RT 1974), concerned only new residential buildings. A second, third and fourth followed, (respectively in 1988, 2000 and 2005) setting more stringent standards and progressively extending the regulation to buildings in the service sector. The regular tightening had a traceable impact on the efficiency of the stock (2,9 % final energy consumption reduction in 1973-1993, despite a nearly 50 % increase in building surface, Martin et al. (1998)).

The last one, the RT 2012, is the result of the national debate on environment and energy (the "Grenelle de l'environnement") in 2008. One of the broadest agreements of the Grenelle de l'environnement has been to set future requirements at ambitious levels, with the current building codes set as milestones toward more stringent regulations.

The thermal regulation for existing buildings sets different standards for the total energy consumption of refurbished buildings above certain thresholds and the energy efficiency of specific items (e.g. windows) in other buildings. It was set up in 2005, along with the previous regulation on new buildings, in order to comply with the Energy Performance of Buildings European Directive (EU 2012).

#### 4.2.3.4 *The Sustainable Development Tax Credit*

The Sustainable Development Tax Credit (CIDD) gives a tax rebate to landlords or tenants for the purchase of energy efficient durables, with rates ranging from 15 to 50 % of investment cost. This scheme was started in 2005 and grew until, in 2008, it benefited 1.4 million households and cost €1.9 billion for an equivalent subsidy rate of 32 % (Insee 2010, CGDD 2012). Eligible technologies were modified and subsidy rates decreased several times since then, in particular in order to reduce the cost for the public budget and to target the best energy efficient durables.

#### 4.2.3.5 *The zero-rated eco-loan*

The zero-rated eco-loan (EPTZ) allows landlords or tenants to have a preferential loan when they invest in a series of energy efficiency measures. Launched in 2009, the scheme has benefited 40,755 households in 2011 (compared to 80,000 in the first year, and to an objective of 30,000 per year in 2013), for an average investment of €16,992 per dwelling (SGFGAS 2012). It promotes refurbishment bundles, with the rationale that many energy efficiency measures are most effective when conducted together with other measures. Giving additional credit possibilities to investors allows landlords or tenants to conduct all efficiency measures as a whole, thus optimizing e.g. a new boiler to a newly insulated home.

## 4.3 WHAT DID THE FRENCH INSTRUMENTS EFFECTIVELY ACHIEVE?

As the previous section highlights it, even if all contribute to reach the overall long term climate objective, policy instruments are the result of a long history, and were set up to achieve given sector-specific targets. Regarding the emission reduction objective, the global efficiency problem can be split into three questions: (i) How effective were the individual instruments to meet their specific objective? (ii) How effective were these instruments in mitigating GHG emissions? (iii) Were they cost-efficient?

Section 4.3.1 answers the first question, and shows that the scope of the carbon price signal is limited in France, therefore leaving space for emission reductions from other instruments. Section 4.3.2 discusses the second question. While the effective abatements achieved by additional instruments are difficult to assess, Section 4.3.3 discusses the possible negative interactions that occurred between emission reductions, the carbon price and additional instruments, and argues that they were minimal.

### 4.3.1 Assessing the effectiveness of individual instruments

#### 4.3.1.1 *Was the EU-ETS effective to reduce emissions?*

As for any policy assessment, constructing the counter factual scenario against which to assess emission reductions induced by the EU-ETS is a thorny exercise. There is a consensus in the literature to conclude that the EU-ETS led to effective though small mitigation during the first phase (peer-reviewed quantified studies are scarce, see Anderson and Di Maria (2011), Delarue et al. (2008), Ellerman and Buchner (2008)). They find respective abatements for Phase 1 of 120-300 Mt$CO_2$ 247 Mt$CO_2$ and 150 Mt$CO_2$ ( the latter only for the power sector), corresponding respectively to 1.9 %-4.9 %, 4.0 % and 2.4 % of the global cap.

Things are more confused for the second phase, where the exceptional economic recession makes the counter factual scenario questionable. Laing et al. (2013) review the gray literature and conclude that the EU-ETS has driven around 40-80 Mt$CO_2$ of annual abatement for Phase 1 and 2, or 2 %-4 % of the total capped emissions. They remain ambiguous on the contribution of offset credits in this evaluation.[8] During the period 2008-2011, 556 million of these credits were delivered (Sandbag 2013), corresponding to approximately 7 % of the cap. Their actual performance in terms of abatement is unclear. Some projects were non additional, and the abatement induced by part of others were most probably overestimated (Zhang and Wang 2011), though the exact quantification of this overestimation is contentious (Schneider 2009). The partial amendment of the allocation rules for the third phase (ban of offset credits coming from industrial gases, origin centered on least developed countries only, smaller amounts authorized) will most likely no be sufficient to absorb the allowance surplus.

Another related question is whether the EU-ETS effectively incentivized long-term investment and innovation in low-carbon technologies over short-term fuel-switching and energy conservation (Newell et al. 2013). A series of managerial surveys gives contrasted results and suggests that overall the EU-ETS has affected investment decisions but in a very limited way (Aghion et al. 2009, Martin et al. 2011, Rogge et al. 2011). Using low-carbon technology patents data, Calel and Dechezleprêtre (2012) find that the EU-ETS had a small but positive effect on innovation.

#### 4.3.1.2 *The scope of the carbon price signal is limited in France*

There is now only hardly a carbon price signal in France. The idea of a relatively high social value for emissions is widely spread (Quinet et al. 2009), but several attempts of setting a carbon tax failed because of political arguments over redistributive issues (Combet 2013).Maybe because of these repeated failures, virtually no other instrument sets a price on GHG emissions, except the EU-ETS covering only 38 % of total French $CO_2$ emissions (Keller 2010).

8. Offset credits (Certified Emissions Reductions CERs issued in Clean Development Mechanism projects CDMs, and Emissions Reduction Units ERUs issued in Joint Implementation projects JIs), were not allowed during Phase 1 so the above-mentioned studies do not take them into account.

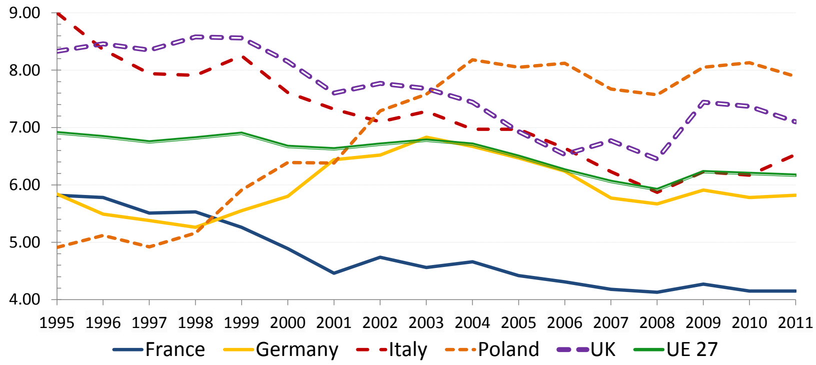



**Figure 4.4:** Environmental taxation as a percentage of total tax revenues in the major European Union member states. Source: Eurostat (2013)

Except some attempts in the industry and agriculture sector (with some domestic credit projects), the price on carbon comes from the EU-ETS in France, and depends on decisions made mainly at the EU level. There are historical taxes on fuels, which affect the consumption and emissions for heating in the residential sector, but there are also numerous tax exemptions (MBCPCRE 2011) which limit the potential of fuel taxation and provide negative incentives for mitigation.

The Cour des Comptes (2011) estimated to approx. €2 bn the gains for the public budget from removing taxes having a perverse incentive on pollution. The landscape of alternative environmental taxation is also very limited. The total environmental taxes amount to 2 % of GDP, or less than 4.5 % of total tax revenues, making France rank 21 of 27 European countries in environmental taxation (see Figure 4.4). They have moreover been decreasing over the past decades, contrary to the European trend (staying more or less constant) and countries such as Germany or Poland.

The EU-ETS covers all the emissions of the electricity sector, with an annual allocation of 25.6 Mt$CO_2$ for the second phase. The carbon price should then allow at least to decentralize abatement decisions linked to electricity consumption, given a relatively high $CO_2$ cost pass-through to electricity prices (Sijm et al. 2006) (although it seems to depend on the time of the day, or whether it is a peak-hour and on the variability of the fuel prices (Jouvet and Solier 2013)). This is not the case in France, where 93 % of all consumers are still under regulated tariffs, inherited from the historical state monopoly (CRE 2012). More than two thirds of total electricity consumption and 94 % of electricity consumption in the residential sector are not impacted by any EU-ETS price signal.

In the absence of such a transversal price on emissions, mitigation relies on complementary policies only. France lacks a truly efficient mean of limiting emission on a large scale. Much potential is left untapped, and which option would be the most efficient is not well known by public authorities as information remains private. This leaves the field to *ad-hoc* negotiations and regulations in each sector.

#### 4.3.1.3 *Were REP promotion instruments efficient in developing green capacity?*

The effectiveness and efficiency of tenders is difficult to establish, as no significant assessment has been made and only some of the various tenders have effectively led to capacity installation. Theoretically, they are similar to FiTs in terms of static and dynamic efficiency (Butler and Neuhoff 2008), except that they should allow revealing more private information by incentivizing the smallest possible bid. They give an incentive for increasing the output of renewables, therefore promoting innovation and correct management. Compared to FiTs they do not necessarily favor the emergence of new bids, and they can lead to opportunistic behaviors, when investors deliberately underestimate their bid price to be selected because they have no threat of penalty in case of failure to deliver (Finon and Perez 2007).

FiTs are efficient in the sense that they equalize the marginal costs of all REP sources for each technology (Couture and Gagnon 2010). They are however different from one technology to another, which could be justified by their variable learning spillovers and variable environmental externalities. The most profitable sites are equipped first and operators have an incentive to maximize production (e.g. by avoiding shades on PV panels). Turbine producers and construction services contribute to most of the costs, and face at least equal levels of competition under the FiT than without (Butler and Neuhoff 2008). From a dynamic point of view, there is a clear incentive to improve existing technologies and introduce new and more efficient ones (del Río González 2012). Any breakthrough (e.g. a new type of solar) with high initial costs and high progress potential would need a tariff on its own however.

Jenner et al. (2013) provide an econometric analysis of feed-in tariff policy effectiveness in Europe. They use the return on investment (ROI) provided by FiTs as a measure of policy strength. They show that on a European scale, FiTs policies have driven solar photovoltaic capacity development in Europe, but results are less clear for wind. For this more mature technology, market factors seem to have had a more pronounced effect on the ROI. Their results also imply that the market context and the policy design are sometimes more important than the mere existence of a policy, i.e. a poorly designed policy is not necessarily better than having no policy at all.

Figure 4.5 show the country-specific trends of added wind and solar capacity and of the ROI of these two technologies from 1992 to 2008, for France and the biggest member-states. Italy and Germany have FiTs since respectively 1992 and 1990, France since 2003 whereas the UK and Poland have had a quota scheme since respectively 2002 and 2008. With the highest ROI since the nineties, Germany clearly had the fastest increase in renewable capacity. The other countries have a negative return until 2004-2005, when the level of the FiTs started growing to give a decent support.

Political inertia has made it difficult for regulators to adapt the level of the tariff fast enough for the technologies with the highest technical progress. The history and Figure 4.5 show that renewable capacity only started growing when the support level started reaching levels sufficient to offset investment risks. Even now, the trend will not allow fulfilling the 2020 targets, not to say the more ambitious 2050 targets.

Recent history has shown that tariff levels were equally slow to follow costs decreases as learning-by-doing started accumulating. This has led to big windfall profits for investors in the periods where the tariff was still high and the costs had decreased sharply.

#### 4.3.1.4 *Were EE instruments effective in reducing energy consumption?*

As a market-based scheme designed to promote the cheapest technology first, EECs are cost-effective. Building standards set a clear reference, and additional instruments help overcome some specific market failures and in-

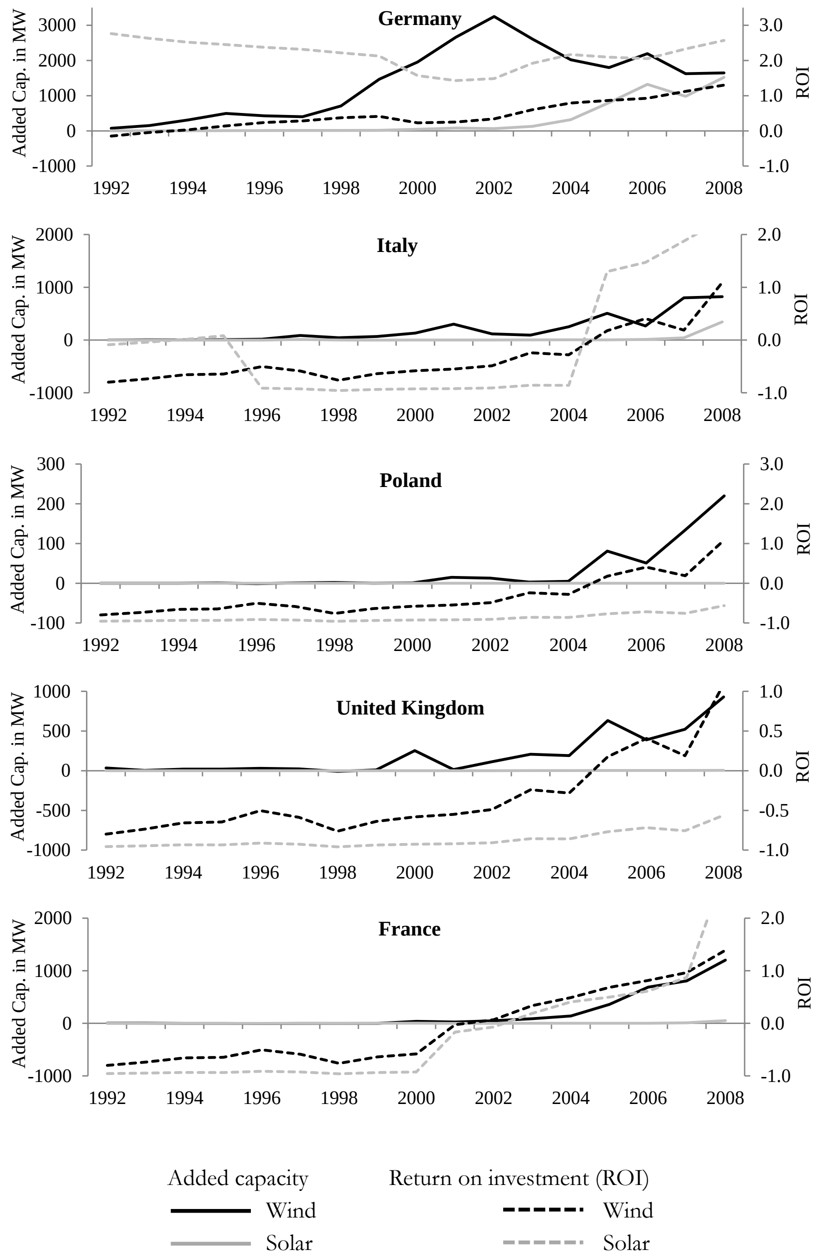



Figure 4.5: Added capacity and return on investment (ROI) values for the biggest member states, for wind and solar, 1992 to 2008. ROI embed policy components (e.g. FiTs levels) as well as other non-policy country-specific components. Source: Jenner et al. (2013)

vestment hurdles in the household sector. Results from the first EECs phase also show that targeted consumption reductions were overshot.

However, despite a developed policy landscape, models show that it falls short of reaching the assigned target of a 38 % reduction in 2020 (Giraudet et al. 2011, MEDDE 2012), and some instruments are not very cost-effective, such as the sustainable development tax credit which does not necessarily reflect the marginal cost of consumption reductions. In a technical note from the French Institute for Statistics and Economic Studies (Mauroux 2012), Amélie Mauroux argues that the average shadow value of the investment attributable to the tax credit was below the social value of carbon (as defined by the Quinet et al. (2009) report, i.e. €32/t $CO_2$).

The scheme also lacks environmental effectiveness, with potentials largely untapped, but mainly because of high cost levels (especially in refurbishing old buildings). Moreover, this policy landscape fails to deal effectively with the rebound effect, with more efficiency measures and almost no sufficiency measures (measures aiming at reducing the consumption of energy services), such as effective feedback to households about their consumption, more information about available technologies and energy taxation.

The dynamic efficiency of the whole mix is also unclear. No study has been made yet to disentangle the effects of the EEC vs. other incentives and regulations (see below) on the choice of investment in efficient technologies. Moreover, the major players (EDF, GDF SUEZ) are inclined to play strategically, by pushing some technologies to be certified as a standard action for certificate issuance. Some technologies (e.g. low temperature boilers) have been authorized while they were less efficient than others (e.g. condensing boilers), probably to sustain to some extent the consumption of one type of energy (electricity vs. gas).

The list of eligible technologies is revised at least every three years, giving some flexibility over the long run. Building technologies are not expected to evolve very rapidly (compared to REP technologies for instance). It is more relevant to assess the dynamic efficiency of this instrument (and the other energy efficiency instruments) in terms of changes in the retrofitting industry. Along this criterion, the EEC have been quite effective. These aspects are also promoted by information and formation campaigns, with possible positive interactions.

There is a debate among economists regarding the static and dynamic efficiency of regulation and performance standards for EE. Some argue it reduces the available options, whereas other back the hypothesis that regulations act as an incentive for regulated entities to support the diffusion of efficient technologies at the lowest possible cost (see Giraudet and Finon (2011) for a discussion). Considering the gains in terms of reduced emissions, and considering other market failures tackled by this instrument (such as the landlord-tenant dilemma, or the energy-efficiency gap), the construction of additional costs from the RT 2012 is limited (approx. +5 % according to Giraudet et al. (2012b)).

### 4.3.2 How much emission reductions did non-ETS instruments bring?

Estimating the emission reductions brought by mitigation instruments other than the EU-ETS is tricky for two reasons. First, one has to know the extent to which the various instruments really induced new REP production or

EE.[9] Second, one must know to what extent these REP productions and EE substitute to fossil production. In general, rebound effects reduce the *ex-post* efficiency of instruments, so that a simple counting of new REP capacity or reduced consumption compared to before the implementation date of the instruments is inaccurate. The actual REP production or EE attributable to instruments should therefore always be careful.

Numerous *ex-ante* studies on REP and EE instruments exist, and have been discussed in previous sections. Extensive *ex-post* studies on REP instruments made on reliable data for France are inexistent, because of the reduced period these instruments were in application, compared to e.g. the German FiTs. Some estimates exist for EE instruments, especially for building codes and white certificates (see e.g. studies by Martin et al. (1998), Mauroux (2012) previously discussed).

Once REP production and EE can be attributed to specific instruments, actual emission reductions through reduced fossil electricity production is an other difficult matter. The effectiveness of one MWh consumption reduction or one additional renewable MWh produced strongly depends on the time of the day and generally on the marginal technology at the time. This is especially important in France, where the emission intensity of the marginal production can be up to six times higher than the average emission intensity of electricity production (Cros and Tabet 2000), due to the high share of carbon-free base generation.

### 4.3.3 Have climate and energy instruments had antagonistic effects on emission reductions?

The equimarginal principle imposes to equalize the marginal abatement effort across the economy to minimize the total abatement costs. This is best done by decentralizing all abatement decisions by creating a price signal, either reflecting the social value of emissions (Perrissin Fabert et al. 2012), or the equilibrium of supply and demand in an emission allowance market such as the EU-ETS.

The multiplicity of targets and instruments has therefore raised criticisms over concerns of antagonistic interactions between instruments and even inconsistencies between targets. Some economists argue that multiplying sector-specific mitigation targets and instruments will generate costly economic distortions by cumulating discrepant implicit mitigation prices (see e.g. Böhringer et al. (2009b), Boeters and Koornneef (2011), Flachsland et al. (2011), Hermeling et al. (2013), Tol (2012)). Other fear that too many instruments will scatter possible policy intervention, bringing too much complexity and possible rent-seeking behaviors (Helm 2010). A prominent conclusion of the economic literature on climate and energy policy interactions is that negative policy interactions should be prevented by reassessing the sectoral mitigation targets toward more consistency (see e.g. Götz et al. (2012)).

#### 4.3.3.1 *The multiplicity of targets reveals different embedded ambition levels*

The various targets for 2020 reveal different embedded ambition levels for emission reductions. The EU-ETS has been prone to intense lobbying from carbon-intensive industries (Markussen and Svendsen 2005), concerning the

9. While it is reasonable to assume that FiTs induced most of the once immature REP technologies (wind, solar), the counter-factual scenario is much more difficult to establish for EE (Baudry and Osso 2007).

allocation method, the scope of the cap, the possible offset methods, etc. The main effect of this lobbying was to lower the ambition of the emission reduction target embedded in the instrument. The emission reduction targets embedded in the REP and EE targets are more in line with the long term mitigation objectives. This resulted in a discrepancy between the apparent implicit marginal cost of emission reductions of REP or EE instruments and the allowance price of the EU-ETS. Another consequence was the relative ease with which the intermediary emission reduction targets were achieved with all instruments in place, and the resulting relative low emission allowance price.

#### 4.3.3.2 *Additional instruments contributed to emission reductions, but interaction effects on emission reductions were minimal*

Section 4.3.1.1 concluded that the EU-ETS induced indeed some emission reductions. In the absence of a comprehensive quantitative assessment, it is difficult to establish by how much additional instruments added to these emission reductions. When assuming a binding cap on emissions, adding instruments in the electricity sector brings no additional abatement. Additional instruments may bring abatements in sectors not covered by the EU-ETS, e.g. by reducing the use of fossil-fuel for heating, or by increasing the share of renewables in the transport sector, but any fossil-fueled electricity consumption reduction either through REP or EE promotion will be matched by a corresponding emission increase in another sector or another country covered by the EU-ETS.

Chapter 1 points out the common feature of instruments promoting REP and EE: they reduce the residual quantity of electricity produced by pre-existing fossil-fueled technologies. This reduces the demand for emission allowances and thus the EUA price as emitting peak-hour capacities are crowded out by renewable energy. The effects of French instruments on this European price are difficult to establish, and no comprehensive quantitative study has been made in France to assess these effects.

Studies do exist at the European level and for Germany however (to cite only one: Böhringer and Rosendahl (2011)). The effect of such interactions is however likely to be smaller in France than in Germany, as less REP capacity has been added in France, and according to calculations from the Caisse des Dépots (Trotignon and Delbosc 2008), only a quarter of the total allowances went to the power sector (approx. 115 Mt $CO_2$) for the first EU-ETS period in France, compared to 60 % in Germany (approx. 890 Mt $CO_2$).

Finally, the previous section stressed the little scope of the carbon price signal on electricity end-users. Although REP and EE instruments had some interaction effects on the carbon price, the interaction effects on the allowance price most likely did not change the consumption behavior of residential or even small non-residential electricity consumers.

#### 4.3.3.3 *Interactions had impact on the electricity supply side*

Although they probably did not affect the demand side, the depressing effect of REP and EE policies on the allowance price from the EU-ETS most likely affected the supply side, by sometimes modifying the merit order of production.

Figure 4.6 shows the technologies used for electricity production during two weeks in April 2011 and April 2012. One can see that gas (in pink) is preferred over coal (in green) and chosen first in 2011, while the opposite

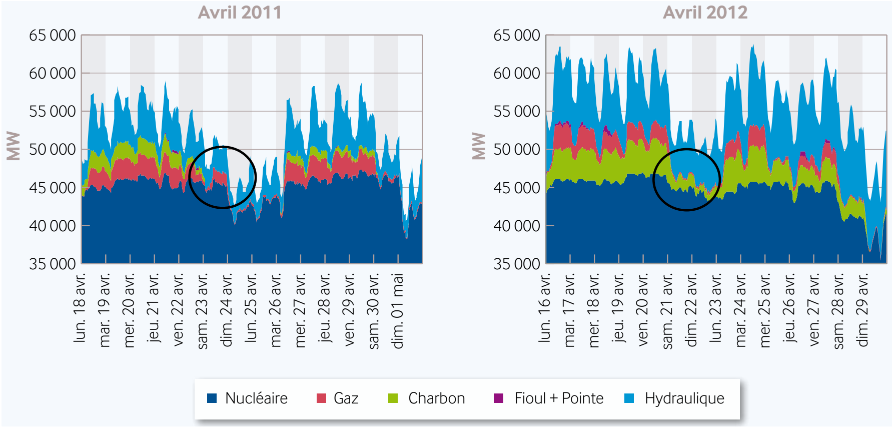



**Figure 4.6:** Technologies used to satisfy the electricity demand, net of distributed renewable production, during the second half of April 2011 and April 2012. Notice in the circle the inversion of merit order: in 2011, gas was used first whereas in 2012, coal was used first. Source: RTE (2012)

is true in 2012. This effect is most visible during the first week-end, when only part of the fossil capacity was necessary to comply with the demand. In 2011, 1.6 GW flexible peak-hour capacity was necessary, and gas provided all of it. In 2012, 1.9 GW was necessary and only coal was used instead.

The gas power plants had a competitive advantage in 2011 they lost in 2012, the "clean dark spread" of coal (electricity price minus production costs including carbon emission costs) being superior to the corresponding "clean spark spread" of gas). This inversion of merit-order is partly due to the fall of coal prices, as US coal was shipped to Europe during the shale-gas production burst, compared to relatively constant gas price, tied by long-term contracts. This inversion is also partly due to the drop of the carbon price, from €17/t$CO_2$ in April 2011 to €7/t$CO_2$ in April 2012, following increasing trends in REP and EE production and expectation of increasing allowance surpluses (see discussion in Section 4.4.1.1).

Interactions may occur on other markets than the EU-ETS or the electricity market. In the EE market both electricity-powered appliances and fuel or gas-powered appliances can be promoted, e.g. when replacing a boiler. Electricity consumption reductions have an effect on the total emissions from electricity producers, which are covered by the EU-ETS, whereas gas and fuel consumption reductions lead to emission reductions not covered by the EU-ETS, and both are treated the same way in terms of EEC.

Renewable energy and energy efficiency measures may have antagonist effects, channeled through the electricity market. For a given energy service demand, the need for renewable energy is reduced when expanding energy efficiency investment decrease the quantity of electricity effectively consumed. On the opposite, promotion of renewable energy makes energy efficiency less attractive by reducing the electricity price (see discussion in Chapter 1). Energy consumption reductions also reduce the need for REP (but no assessment has been made of this effect in France). Depending on the consumption reductions and on the demand function, EE reduce the ability of the electricity system to absorb the variability of REP production, thus reducing the maximum share of REP that can be added to the system (Jonghe et al. 2011). In households, energy efficiency instruments promote some REP technologies, but with no real emphasis on those technologies. There is no scheme giving a strong incentive (from a static or dynamic perspective) for developing efficient REP technologies for households, and a potential for positive interactions is left untouched.

#### 4.3.3.4 *Future interactions depend on the nature of the carbon price signal*

As discussed in Section 4.2.1, France experienced several attempts of setting a tax on the carbon content of energy. In the meantime, negotiation continue on the future of the EU-ETS, with the possibility of permanently removing some of the emission allowances in excess.

In the event of a future carbon price signal substantially higher than the current one, the possible interaction with the other instruments already present would depend on the nature of this signal. If resulting of the EU-ETS emission allowance price, other instruments could not claim as many additional abatements any more, since their effect on renewable production and electricity demand would probably be much less negligible. By substituting with the fossil electricity production, they would reduce the carbon price (see Chapter 1) and undermine the efficiency of the policy mix by increasing compliance costs without bringing as much emission reductions.

If the high enough carbon price results from a tax, interactions would be fundamentally different, because in this case, emission reductions are additional. Additional instruments may not be as efficient as a pure and high enough carbon tax alone, but they do not bring only additional costs, they help achieve some of the abatements needed for a long term transition target.

## 4.4 ECONOMIC RATIONALES FOR COMBINING INSTRUMENTS

As discussed previously, French climate and energy instruments are the result of a long and complex history. Each one of them was set for a specific objective, but even though they were not designed to operate as a whole, interactions between instruments remained minimal. As emission reductions brought by non-European Union Emission Trading System (EU-ETS) instruments in the past are difficult to establish, one has to consider the different rationales from the economic literature to assess the climate-energy policy mix as a whole. To what extent do these arguments, and the arguments from other chapters in this thesis, provide a justification for keeping a combination of instruments in the French climate and energy policy mix to reach long term emission reduction objectives, and what instruments should this mix contain?

### 4.4.1 The risk of a nil or very low carbon price justifies combining instruments for mitigation

#### 4.4.1.1 *The EUA price is uncertain*

The history of the EU-ETS since its introduction in 2005 shows how volatile the carbon price can be. It dropped to virtually zero in 2007 because allowance allocation in Phase 1 was too generous (Ellerman and Buchner 2008), recovered up to more than €30/t$CO_2$ because allocation in Phase 2 was tighter and dropped again sharply in 2009 following the economic cri-

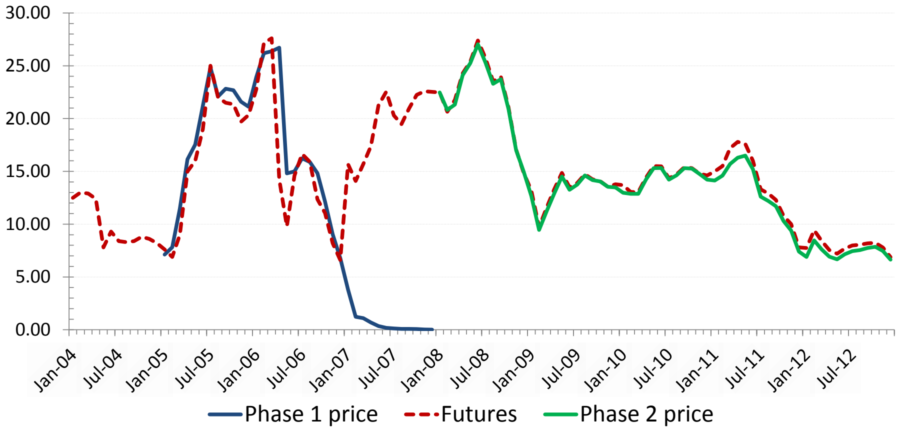



**Figure 4.7:** First and second phase EUA prices and futures price (monthly average). Source: Sandbag (2013).

sis and several additional policy announcements (such as the Renewable Energy Directive in 2009), down to €3/t $CO_2$ in April 2013 (see Figure 4.7).

The economic crisis dramatically affected the construction sector and the automobile industry, in turn affecting steel and cement production which are the major non-electric EU-ETS covered sectors. The economic slow-down also affected the electricity demand, which fell by nearly 5 % between 2008 and 2009 (ENERDATA 2013). Since 2009, emissions of EU-ETS sectors are widely lower than the number of allocations, increasing year after year the surplus of allowances. Neuhoff et al. (2012) estimate this surplus of allowances to rise to 2.7 billion tonnes by 2013, and to last beyond the end of the third phase.

With such an excess of supply, and because supply is so rigid, the allowance price reflects the expectations of EU-ETS participants on the climate policy stringency after 2020 and the possibility of public intervention designed to restore the European emission allowances (EUA) price. This fact is common to all pollution allowance markets, and many emission trading schemes have low or nil prices (see Tab. 4.2).

Neuhoff et al. (2012) add another interpretation for the price variations in a situation of surplus: they reflect the higher expected returns of speculative investors entering the market. If expectations about a future policy interventions and the allowance surplus stay constant, new market participants entering the allowance market with higher return expectation will make most of the transaction volume. The price of allowances will drop until they meet the higher discount rates of those new participants. These higher discount rate may further reduce the feasibility of abatement projects, calling for specific ETS designs limiting the accumulation of allowance surpluses.

#### 4.4.1.2 *With a nil carbon price, alternative instruments set a positive carbon shadow value*

As Chapter 2 points out in presence of a risk of a nil carbon price, the second best optimal mitigation effort is shared between the carbon price and an alternative instrument, e.g. a renewable energy power (REP) subsidy. [10]

10. This alternative instrument could very well be a price floor, an incentive for energy efficiency (EE) or an adjustment of the emission cap. The point is that a minimum mitigation effort is carried through.

Table 4.2: Incidence of low prices and nil prices in emission trading schemes

| | | |
|---|---|---|
| EU-ETS Phase 1 | The price dropped to zero | Ellerman and Buchner (2008), Kettner et al. (2008) |
| EU-ETS Phase 2 | The price would have dropped to zero without banking | |
| Regional Greenhouse Gas Initiative | The cap was higher than the emissions (phase one carbon emissions fell 33 % below cap), so the price dropped to the price floor | (Point carbon 2012) |
| US $SO_2$ ETS | The cap was higher than the emissions (new regulations + decrease in high-sulfur fuels consumptions) | Schmalensee and Stavins (2012) |
| EU-ETS Phase 3 | The allowance surplus increased beyond hedging needs for future production | Neuhoff et al. (2012) |
| Chicago Climate Exchange (voluntary ETS) | The price dropped to virtually zero in 2010 | Kossoy and Guigon (2012) |

In this respect, the French non-EU-ETS mitigation instruments may be justified because they incentivize emission reductions even in the absence of a positive carbon price.

### 4.4.2 Even in presence of a Pigovian carbon price, additional mitigation instruments may be justified

#### 4.4.2.1 *Multiple instruments to reach multiple targets*

Jan Tinbergen states in his 1952 book *On the Theory of Economic Policy* that policy makers should not use less policy instruments (*political parameters* in his terms) than targets pursued (*target variables* in his terms) in order to avoid trading-off one target for another (Knudson 2009, Tinbergen 1952).[11] A good practice rule, dubbed *Tinbergen rule*, was later derived from this statement, requiring a bijection between targets and instruments, and in particular that in order to reduce emissions from a given source not more than one instrument should be used (Böhringer et al. 2009a). This rule does not hold when one considers the additional targets usually accompanying the French emission reduction target as justified (Braathen 2007, Del Rio and Howlett 2013).

This merely shifts the question of why such targets in the first place. Various drivers prevail for the setting of climate and energy targets, potentially explaining the existence of multiple targets. For example, the French official programs for REP and EE promotion are not only justified on the ground of fighting against climate change, but also as a mean to enhance energy security, to foster technology development and to reduce the burden of energy expenses on households (MEDDAD 2007, MEDDTL 2011). Multiple targets thus appear as trade-offs between several political objectives. This however does not presume whether targets are well chosen or not, and if they allow for good policy making.

11. And not the opposite, as is often argued in the literature on optimal policy choice.

#### 4.4.2.2 *Rationales for additional instruments for mitigation*

Other rationales justify the use of a combination of instruments, even when a long-term mitigation target is considered in isolation. The first group of rationales relates to the static efficiency of the overall instrument mix. Market failures can impede the proper functioning of energy markets, energy efficiency markets (Gillingham et al. 2009, Sanstad and Howarth 1994) and market-based instruments such as the EU-ETS (Ellerman et al. 2010). The existence of information problems, incomplete property rights, market power, high transaction costs and in general the lack of cost pass-through from the EU-ETS to energy prices, can thus justify in themselves the addition of specific instruments (Bennear and Stavins 2007, Fischer and Preonas 2010, Goulder and Parry 2008, Levinson 2011, Sijm 2005).

The second group of rationales relates to the dynamic efficiency of the instrument mix. Optimally, the mix should allocate abatement efforts across sectors and actors, but also in time. It should incentivize current and future least-cost options. Learning spillovers can be considered as dynamic externalities. R&D investment in renewable energy has a high degree of uncertainty, as well as limited appropriation and large economies of scale. Each factor can cause the private sector to under-invest in renewable energy R&D, thereby limiting technological progress and future cost savings (Fischer and Preonas 2010, Goulder and Parry 2008). This provides a justification for implementing instruments specifically promoting learning-by-doing and R&D (Goulder and Mathai 2000, Stavins et al. 2004). Fischer et al. (2012), by using a model of the electricity sector featuring a climate externality, learning and R&D spillovers for REP and limited appropriation of the benefits from EE, argues that the optimal mix should contain a carbon price inducing most of the emission reductions, subsidies for REP production and innovation to address respectively the learning and R&D spillovers, and a subsidy for consumption reductions to induce enough investment in EE.

As discussed in Chapter 3, the presence of congestion effects in the investment supply chain, or the scarcity of skilled labor and available capital, may be considered an externality as well, in presence of limited foresight or imperfect anticipation. Moreover, many high-potential abatement options can only yield efficient abatements if widely spread or linked with costly infrastructure, suggesting network externalities or huge economies of scale. Many have a high inertia, meaning that they can only yield their long-term potential if investment start now. The failure to trigger such investment may provide a case for additional coordination.

### 4.4.3 Future benefits from climate and energy policies are uncertain and difficult to assess

The difficulty to assess the future benefits from climate and energy policies stems from several factors. Future benefits rely on uncertain parameters, from the feasibility of ambitious targets and instruments, to the level of economic activity. As discussed above, these deep uncertainties impact the EUA price, which in turn impact the profitability of short term mitigation options.

Moreover, large scale options such as carbon capture and storage (CCS), new generation nuclear, smart meters, etc. might benefit from large economies of scale, and will have an impact only if widespread. The synergies between mitigation options are especially difficult to assess, but may reveal as crucial to achieve ambitious long term mitigation targets.

One further challenge of climate policy is to resolve the gap between short term and long term action. Chapters 2 and 3 address these two aspects. On one hand, the incentive for immediate action, i.e. the shadow value of emission reductions or the social cost of carbon, should be high enough to tap the current cost-effective potential. On the other hand, correctly anticipating the future climate constraint is essential, in order to adjust correctly the current effort to minimize the total congestion costs that may appear to be substantial. in other terms, the success of the overall mix depends on both short term decisions and the enabling of long term options.

This echoes the analysis by Grubb et al. (2014), defining a *strategic investment* and a *markets and pricing* pillars, along which the regulator should develop the policy mix to achieve efficient long term emission reductions. Private actors are best placed to take short term investment decisions, but may not be able to set adequate long term targets. The information on technologies and abatement costs is possessed by private actors, hence an efficient climate policy should exhibit a reliable price signal for emission reductions, and let the market decentralize the investment decisions. But due to capital accumulation, many high potential abatement options take long time to build-up, by enabling learning, develop the networks and prepare large-scale diffusion of future zero-carbon technologies. This may best be done by a regulator setting reliable long-term targets for each sector according to its dynamic characteristics (e.g. city planning and transportation take more time to transform than e.g. home appliances).

## 4.5 CONCLUSION: TOO MANY INSTRUMENTS?

A desirable policy mix is necessarily a relative matter. Any given policy can only be defined and assessed according to a specific objective, and has to be measured along a specific target. The various instruments of the French climate and energy policy mix brought some benefits with respect to their specific targets, as highlighted by Section 4.2. Those targets, and thus the corresponding instruments, where however set up without general plan, for individual and sometimes conflicting objectives. This chapter investigates whether taken as a whole, they may actually be efficient and ambitious enough to reach the ambitious long term French target of reducing its greenhouse gases (GHG) emissions by 75 % by 2050.

*The scope of the carbon price signal is limited in France, justifying additional instruments*

The first observation one has to make on the French climate and energy policy mix is that despite several attempts of setting a carbon tax (or equivalent), there is virtually no carbon price signal in France. The EU-ETS is the only instrument pricing carbon, allowance prices reach historically low levels, and electricity prices are in any event largely regulated. This leaves space for additional intervention in order to reach the official long term targets.

The French electricity production being already largely decarbonized, additional abatement efforts will have to tap into more remote potentials than the fuel switch often carried out in other European states. Reaching an almost carbon-free electricity production will therefore necessitate substantial investment in carbon-free electricity generation technologies or in energy efficiency technologies. Those technologies are not yet competitive, and may need some incentives to be deployed.

*Current instruments are moderately effective to achieve the French long term emission reduction target*

The French climate and energy strategy is split into a multiplicity of targets and specific instruments. Instruments are designed for achieving their specific objectives, and are only moderately efficient in achieving additional emission reductions, and this even though they cause only very little negative interactions with each other.

Achieving the other targets of the French climate strategy could help achieve the overarching long term abatement objective. But the current refurbishing rates of public and private buildings are not in line with those planned in the thermal regulation law of 2012. Regarding renewables, as the French general public accounting office (the *Cour des Comptes*) puts it, reaching even just the 2020 target will require at least six times the financial effort made between 2005 and 2011 (Cour des Comptes 2013). In comparison, reaching the official 2050 GHG emission reductions objective of 75 % will require an even more intense effort, or a better coordinated policy mix.

*The optimal long term mix contains several instruments, but depends on the carbon price trajectory*

Because the carbon price signal is so low, and for other reasons detailed in Section 4.4, the French policy mix should stay a combination between the EU-ETS and instruments promoting renewable energy and energy efficiency. In fact, an instrument combination would be justified even for a Pigovian carbon price.

The ideal policy mix depends however on how the carbon price signal will evolve, and on the type of instrument that will set it: tax or cap? If close enough to the social cost of carbon, a carbon tax or a credible EUA price would trigger most of the short term mitigation options available, and influence most of the anticipations of investors for the future stringency of climate policy. Additional instruments should then only address additional externalities and market failures: (i) information programs, facilitated access to capital for efficiency investments and training future efficiency appliance installer's to address the various market failures of EE markets (especially the refurbishing of buildings); (ii) production and R&D subsidies for immature technologies to address positive learning spillovers; (iii) clear long term targets, reliable and ambitious emission constraints, transparent energy markets and support for capital intensive carbon-free technologies in early stages of the transition to correctly anticipate congestion costs and enable long term potential options.

A large removal of allowances is however still out of reach, and the level of the tax proposed by the current government is still much lower than the social value of carbon identified by several reports from the French administration and is still likely to be lowered to satisfy possible lobbying activity.[12] A lasting low carbon price signal may justify higher ambitions for additional instruments, and would justify relatively high abatement shadow prices, comparable to the level of the social value of carbon emissions (even

12. €7 to €22/t$CO_2$ in 2015, compared to the €32/t$CO_2$ to €200/t$CO_2$ in 2050of the Rapport Quinet (Quinet et al. 2009).

though Chapter 3 has shown that these metrics are misleading, and that congestion effects may lead to underestimate the optimal level of shadow costs because they ignore dynamic effect).

Instruments such as the energy efficiency certificates (EEC) scheme tend to trigger the least-cost options first, thus would efficiently complement or replace the carbon price. If managed well and adjusted to the maturation of each technologies, feed-in tariff (FiT) can also efficiently complement a carbon price to enable additional learning effects, and enable enough investment for ambitious long term mitigation targets. Chapter 2 found that renewable subsidies may be welfare enhancing if the uncertainty on the future level of the carbon price is high enough. Preferential loans, such as the zero-rated eco-loan would also be specially interesting instruments, enabling abatements in a sector having a deep potential but many market failures, and giving an incentive to invest in technology bundles to benefit from synergies between technologies.

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# CONCLUSION GÉNÉRALE

## PRÉSENTATION ET APPORTS DE LA THÈSE

Cette thèse aborde les problématiques du choix optimal d'instruments pour réduire les émissions de gaz à effet de serre (GES) dans le secteur électrique, afin d'éclairer les déterminants de l'efficacité d'un portefeuille d'instruments de politiques climatiques et énergétiques mis en place pour assurer une transition vers un secteur électrique décarboné. Quatre problématiques liées ont été traitées au sein de quatre chapitres relativement autonomes et développant une méthodologie spécifique. La thèse apporte des éléments de réponse à cinq questions transversales.

*Un prix du carbone est-il suffisant pour déclencher une transition décarbonée, dans un cadre incertain et dynamique ?*

De nombreuses circonstances empêchant l'atteinte d'un optimum de premier rang via la fixation d'un signal-prix du carbone sont déjà décrites dans la littérature (présence d'externalités multiples, biais cognitifs, etc.). Cette thèse discute deux défaillances potentielles supplémentaires, découlant de la prise en compte d'une incertitude importante du niveau de la demande d'énergie (entraînant un risque de prix nul du carbone) et de la prise en compte d'effets de congestion dans les investissements du secteur électrique.

Dans un modèle analytique d'équilibre offre-demande du secteur électrique avec un niveau incertain de demande future d'électricité, le Chapitre 2 montre que lorsque cette incertitude est suffisamment élevée, le risque que le prix du carbone sur le marché de permis d'émissions tombe à zéro ne peut être écarté. L'incertitude sur la demande d'électricité induit de fait une incertitude sur le niveau de la courbe de coût marginal de réduction d'émissions pour un plafond donné. Pour des situations où le niveau de cette courbe est très incertain et variable, il peut être plus coûteux de tenter à tout prix de conserver un plafond contraignant quel que soit l'état de la nature. En effet, le surcoût encouru en cas de coût marginal élevé serait prohibitif. Dans certains états de la nature le signal-prix carbone ne fonctionne plus, et le niveau de réduction d'émissions espéré est insuffisant.

Par ailleurs, le secteur électrique est fortement capitalistique, et la dynamique d'accumulation des capacités de production faiblement carbonées est une problématique majeure dans la détermination d'une trajectoire efficace de transition vers une économie décarbonée. Dans un modèle analytique en temps continu du secteur électrique, le Chapitre 3 représente l'inertie induite par l'accumulation de capital et les effets de congestion ayant lieu pour les investissements faiblement carbonés. Ces effets de congestion correspondent au fait qu'il est impossible de remplacer du jour au lendemain l'ensemble des capacités de production d'électricité polluantes par des centrales efficaces et vertes. Ils sont représentés sous la forme d'une fonction de coût d'investissement convexe, et reflètent la rareté de ressources clés comme les travailleurs qualifiés et le capital adapté.

Le Chapitre 3 montre que l'évaluation des investissements, et notamment la détermination du niveau optimal d'investissement ne va pas de soi. Même en présence d'un signal-prix du carbone, il n'est pas possible de représenter de manière explicite les coûts marginaux de réduction d'émissions, ni d'égaliser les efforts marginaux de réduction d'émissions dans le temps et entre technologies. En fait, la minimisation des coûts de congestion tout au long de la transition peut même conduire à un inversement de l'ordre de préférence des technologies : il peut ainsi être plus intéressant de commencer par une technologie plus chère car elle apportera plus de réductions d'émissions tout au long de la transition.

La présence d'un prix du carbone, d'un prix de l'électricité et d'une cible de part de marché finale parfaitement anticipés suffit à déterminer la trajectoire optimale de transition vers une production électrique décarbonée. Le cadre certain utilisé ne met pas en évidence de défaillance du prix du carbone. Le prix du carbone suit en revanche une trajectoire exponentielle, croissant avec le taux d'actualisation : le prix du carbone réel est d'abord faible, puis aumente et devient maximal à la fin de la transition. Cette trajectoire est très différente des trajectoires de coûts marginaux d'investissement, qui ont plutôt une forme en cloche, avec une concentration des efforts d'investissement au début de la transition. Le prix du carbone ne donne pas une bonne représentation du niveau de réduction d'émissions à réaliser.

Même un indicateur prenant en compte la valeur des réductions d'émissions, le coût marginal de long terme ou encore coût unitaire actualisé de l'électricité (LCOE), ne suffit pas pour informer de manière statique et instantanée de la valeur d'un investissement dans une technologie de réduction d'émission par rapport à une autre. Une application numérique au secteur électrique européen montre que sur la trajectoire optimale de transition, le LCOE de la technologie apportant le plus de réduction d'émissions est toujours supérieure à celui de la technologie la plus carbonée. L'utilisation d'un critère incomplet pour comparer les technologies et évaluer les investissements conduit à un sous-investissement dans les technologies dont les effets dynamiques sont les moins biens anticipés. Les résultats suggèrent ainsi que l'utilisation du LCOE pour comparer les investissements en capacités de production au gaz ou renouvelables pourrait conduire à des sous-investissements en renouvelables, du fait des effets de congestion. L'effort marginal de réduction d'émissions est donné par le coût marginal implicite de location du capital, une grandeur comptable égalisant la valeur intertemporelle marginal d'une unité de capital, incorporant le prix de l'électricité et le coût variable de production. Cette grandeur donne une réalité économique au principe d'équimarginalité, mais ne permet pas non plus d'évaluer les investissements d'une technologie particulière par rapport à une autre.

Le Chapitre 4 réalise une évaluation qualitative du portefeuille d'instruments des politiques climat-énergie déployé en France. Il montre qu'en France, les réductions d'émission sont principalement valorisées de manière implicite par des instruments promouvant les renouvelables et l'efficacité énergétique car le prix des permis d'émission est très faible. Mais il n'est pas certain que même un signal-prix du carbone élevé, par exemple si les États européens parviennent à se mettre d'accord sur le retrait définitif de permis d'émissions de l'European Union Emission Trading System (EU-ETS), puisse garantir des décisions d'investissement et de consommations compatibles avec la cible ambitieuse de la France de réduire ses émissions par quatre d'ici 2050. En effet, l'EU-ETS ne couvre qu'une minorité des émissions en France (car la production électrique est déjà largement décarbonée) et ne touche que peu d'acteurs, même dans le secteur électrique, car le prix de l'électricité est encore largement régulé.

*La mise en place d'instruments additionnels de promotion de technologies de réduction d'émissions est-elle justifiée par les défaillances du prix du carbone ?*

Cette thèse met en évidence deux défaillances potentielles du signal-prix carbone non encore traitées dans la littérature : le contexte de forte incertitude sur le niveau de demande d'électricité et les congestions provoquées par les investissements décarbonés. On a vu que la première conduit effectivement à un niveau de réduction d'émissions sous-optimal. La seconde, étudiée dans le Chapitre 3, ne conduit en revanche pas à une situation sous-optimale en raison des hypothèses d'anticipation parfaite et de cadre certain adoptées. Les résultats permettent en revanche d'apporter quelques éléments de discussion quant à des instruments additionnels éventuels.

Le Chapitre 2 montre que dans le cas d'une incertitude élevée de la demande d'électricité et lorsque les émissions sont régulées par un plafond, un portefeuille d'instruments incluant une subvention aux énergies renouvelables est plus performant qu'un plafond d'émission seul pour réduire les émissions de GES. Contrairement à une situation avec une incertitude faible ou nulle, où c'est l'espérance seule du prix du carbone qui est égale au dommage marginal, permettant ainsi d'atteindre un niveau de réduction d'émission suffisant, lorsque l'incertitude est élevée c'est une combinaison linéaire du prix du carbone espéré et de la subvention aux énergies renouvelables qui est égale au dommage marginal. L'effort de réduction d'émission est partagé entre les deux instruments. Une application numérique au secteur électrique européen montre que pour un ensemble raisonnable de valeurs des paramètres, l'ajout d'une subvention aux énergies renouvelables de l'ordre de 3 à 10 €/MWh peut augmenter le bien-être social d'une dizaine à plusieurs centaines de millions d'euros par an.

Le Chapitre 3 montre que c'est la combinaison d'un prix de l'électricité, d'un prix du carbone et d'une cible de long terme parfaitement anticipés qui permettent de réaliser une transition efficace vers une production électrique décarbonée d'ici 2050. Cela met en évidence le besoin d'une vision claire à long terme, et notamment l'importance des cibles de moyen et long terme de type « 3×20 ». Ces résultats suggèrent aussi que dans un cadre plus réaliste où ces cibles seraient entachées d'une part d'incertitude, où elles ne seraient pas partagées par les agents ou bien encore où elles seraient mal anticipées, le prix du carbone ne serait probablement pas suffisant pour garantir une trajectoire optimale des investissements.

Le Chapitre 4 montre qu'en France, les instruments de promotion des renouvelables et de l'efficacité énergétique pourraient remplacer en partie un prix du carbone défaillant, en fournissant une valeur aux réductions d'émissions apportées par ces technologies (même si elle est implicite). Le portefeuille optimal varie en revanche fonction des hypothèses que l'on peut faire sur la trajectoire future du signal-prix du carbone. Ainsi, la mise en place d'une contribution climat-énergie ambitieuse pourrait rendre caduque une partie des instruments en place. Le retrait permanent de permis aurait les mêmes effets, avec comme différence des interactions générées plus importantes, en plafonnant les réductions d'émissions totales réalisables par le secteur électrique et en accentuant les interactions entre prix de l'électricité et subventions pour technologies décarbonées.

*Quelle sont les impacts d'instruments de promotion de technologies de réduction d'émissions ajoutés au prix du carbone ?*

Bien que parfois justifiées par les défaillances du prix du carbone, les combinaisons d'instruments génèrent des interactions parfois néfastes via les marchés de l'électricité et des permis d'émission. Tandis que le Chapitres 2 étudie un cas d'interaction positive entre un plafond d'émissions et une subvention aux énergies renouvelables sur le bien-être social, le Chapitre 1 caractérise quant à lui de manière explicite les interactions entre les instruments les plus communs au sein des portefeuilles de politique climat-énergie européens. Ce chapitre montre au moyen d'un modèle analytique d'équilibre statique du secteur électrique les coefficients de variation des variables endogènes (le prix de l'électricité au consommateur, le prix du carbone ainsi que le bien-être social [13]) en fonction des changements dans les instruments de politique climat-énergie.

Il est montré que pour un tel portefeuille d'instrument, très courant au sein des pays de l'Union Européenne (UE), l'ajout ou l'augmentation du tarif d'achat renouvelables diminue le prix à la consommation de l'électricité lorsqu'on peut faire l'hypothèse que la production d'électricité non renouvelable est indépendante du prix du carbone, et ce en dépit du fait que la taxe à la consommation augmente. Comme le plafond d'émissions fixe la quantité d'électricité fossile produite, l'augmentation du tarif d'achat induit une hausse de la production totale d'électricité. Du fait du caractère décroissant de la disposition marginale à payer, cette hausse n'est possible qu'accompagnée d'une baisse du prix de l'électricité aux consommateurs, en dépit d'une hausse de la taxe à la consommation. La hausse de la production de renouvelables s'accompagne d'un relâchement de la contrainte du plafond d'émissions, ou autrement dit d'une baisse du coût marginal de réduction d'émissions, et le prix du carbone diminue, induisant une baisse plus importante du prix de gros que la hausse de la taxe n'induit de hausse du prix de détail. Ce résultat tient lorsqu'on peut faire l'hypothèse que la production d'électricité non renouvelable est indépendante du prix du carbone. Cela est en particulier faux si on considère plusieurs technologies de production non-renouvelable avec des intensités d'émissions différentes (par exemple s'il y a beaucoup de nucléaire) ou si on considère la possibilité d'améliorations de l'efficacité d'émission de la technologie fossile.

La hausse du tarif d'achat provoque un transfert de la rente carbone vers les consommateurs et les producteurs renouvelables. Cette rente carbone peut revenir aux producteurs fossiles (lorsque les permis d'émissions sont distribués gratuitement) ou bien au régulateur, lorsque les permis sont mis aux enchères. Lorsque les permis d'émissions sont mis aux enchères, le profit des producteurs fossiles est inchangé par le tarif, car la baisse du prix de gros est entièrement compensée par une baisse du prix du carbone. La rente carbone suit de plus une courbe en U en fonction du plafond d'émissions : pour des plafonds relativement bas, l'augmentation du plafond augmente la rente carbone, tandis que l'inverse est vrai pour des valeurs relativement élevées du plafond. Il existe ainsi une valeur de plafond qui maximise les revenus des ventes aux enchères de permis.

Le Chapitre 4 montre qu'en France, il n'y a pratiquement pas eu d'interactions entre EU-ETS et instruments de promotions des renouvelables ou de l'efficacité énergétique sur le prix de l'électricité, du fait du faible niveau du prix du carbone, du caractère régulé du prix de l'électricité et de la faible

13. Défini ici comme l'agrégation du surplus des consommateurs et des producteurs.

part de production d'électricité carbonée en France. Pour les mêmes raisons, les instruments français n'ont probablement que très peu influencé le prix du carbone européen. Il y a eu en revanche des interactions du côté de l'offre, avec probablement quelques inversions de l'ordre de mérite entre capacités de production au gaz et au charbon.

*Quelle est l'efficacité d'un portefeuille donné incluant des instruments de promotion des renouvelables et de l'efficacité énergétique pour réduire les émissions de GES à long terme ?*

Lorsqu'on ne considère qu'un seul objectif, la réduction des émissions de GES, et notamment lorsqu'aucune autre défaillance de marché ne vient compliquer la situation, la politique optimale (de premier rang) consiste en un signal-prix carbone unique égal au dommage marginal occasionné par les émissions. L'ajout d'instruments supplémentaires, par exemple pour promouvoir directement des technologies bas carbone, ne fait qu'augmenter le coût social de la politique. Dans le cas où un plafond d'émissions vient limiter les émissions de GES, non seulement le coût global augmente, mais cela ne provoque aucune réduction d'émission supplémentaire dans le secteur électrique. Le Chapitre 1 montre ainsi que le bien-être social diminue lorsqu'on ajoute une subvention à l'efficacité énergétique ou un tarif renouvelable à un plafond d'émissions.

Dans une situation de second rang en revanche, par exemple lorsqu'une contrainte politique va empêcher la mise en place d'un signal-prix suffisant, le portefeuille de politique optimal dépend du type d'instruments utilisé. Si le signal-prix carbone est déterminé par une taxe, il peut être bénéfique de le compléter par des subventions pour des technologies bas-carbone. S'il est déterminé par un marché de permis d'émissions en revanche, l'existence de ce plafond empêche toute réduction supplémentaire par d'autres moyens, et il n'est pas utile de le compléter par d'autres instruments.

Ce dernier résultat n'est valable que pour un plafond d'émission contraignant. Dans le cas contraire, s'il existe une possibilité que le plafond d'émission ne soit pas atteint, un portefeuille contenant un instrument supplémentaire comme un tarif d'achat par exemple peut être plus efficace, ainsi qu'il est montré dans le Chapitre 2. Le Chapitre 3 montre quant à lui que de manière assez intuitive un prix du carbone associé à une cible crédible et parfaitement anticipée est efficace pour générer des réductions d'émissions optimales.

En France, le Chapitre 4 montre que le portefeuille actuel n'est très vraisemblablement ni assez efficace, ni assez ambitieux pour atteindre les cibles fixées par la loi, que ce soit en termes de réductions d'émissions à 2050 (le *facteur 4*), en termes d'investissement en capital efficace (comme les rénovations de bâtiments par exemple) ou même en termes de niveau d'investissement en capacités de production renouvelables à 2020. Mener à bien une transition vers une production électrique décarbonée en France nécessiterait soit la mise en place d'un signal-prix du carbone assez fort pour influencer les décisions d'investissement et de consommation des agents, soit une refonte partielle des instruments existants pour refléter un niveau d'ambition et une efficacité accrus.

*La France peut-elle se s'affranchir d'une partie de ses instruments ?*

Après avoir réalisé une revue de la littérature sur l'efficacité des principaux instruments de politiques climat-énergie français pris individuellement, puis après avoir estimé l'efficacité du portefeuille dans son ensemble, le Chapitre 4 avance quelques recommandations pour amender le portefeuille actuel. Ainsi que cette thèse le met en évidence, le portefeuille optimal d'instrument ne saurait être constitué d'un prix du carbone unique, fût-il suffisamment élevé, et ce ne serait-ce que parce que la France hérite d'un demi-siècle de politiques climat-énergie et ne saurait faire table rase d'une multiplicité d'instruments déjà en place et dont certains ont fait leur preuves.

Les recommandations possibles sur un portefeuille climat-énergie cible dépendent en revanche des hypothèses sur la trajectoire du signal-prix du carbone. La nature des interactions qui pourraient être générées par une hausse de ce signal-prix vont en effet dépendre de la nature de l'instrument qui le produira : nouvelle taxe liée au contenu carboné de l'électricité ou bien retrait définitif d'une partie des permis d'émissions de l'EU-ETS. Dans le premier cas, les interactions seraient bien moindres et un portefeuille plus étoffé pourrait se justifier. Dans l'éventualité d'une contribution climat-énergie significative en 2015 (comme projeté par le gouvernement actuel), ou bien si les États-membres de l'UE parviennent à se mettre d'accord sur une réforme d'envergure de l'EU-ETS, certains instruments faisant la promotion de réduction de consommation dans le résidentiel ou le tertiaire pourraient se révéler superflus. Un instrument unifié donnant les moyens aux particuliers de réaliser des rénovations d'envergure du bâti existant pourrait remplacer une partie des instruments actuels de promotion de l'efficacité énergétique. Dans l'éventualité d'un signal-prix du carbone durablement faible, des niveaux plus élevés de subvention pour ces technologies d'efficacité énergétique et de production d'électricité à partir de renouvelables pourraient se justifier.

## OUVERTURES

Chacun des chapitres de cette thèse invite à des extensions et des approfondissements. Le modèle présenté dans le Chapitre 1 se prêterait ainsi particulièrement bien à l'étude des interactions entre différentes formes de promotion de l'efficacité énergétique, efficacité des moyens de production ou efficacité de la demande. Une étude approfondie des effets entre différents instruments promouvant l'efficacité ou la sobriété pourrait également être réalisée. L'architecture très souple de ce modèle en ferait un bon choix pour servir de support à une revue de littérature des effets d'interactions, incluant et comparant plusieurs portefeuilles variés d'instruments. L'incorporation de pouvoirs de marché pourrait également se révéler fructueux.

Le modèle développé dans le Chapitre 2 pourrait être étendu à l'étude et la comparaison de l'efficacité de plusieurs instruments différents de promotion des renouvelables en présence d'incertitude : tarifs d'achat, prime ou subvention à la production, certificats verts. On voit que le niveau espéré de production renouvelable dépend des politiques mises en place, qui garantissent un niveau différent de revenu. Il serait intéressant de creuser cette question et d'examiner par exemple les mérites comparés de plusieurs types d'instruments de promotion des technologies vertes pour garantir ce revenu, en fonction de différents types d'incertitudes, régulatoires ou économiques. L'incorporation d'incertitude sur la production renouvelable et d'intermittence pourrait également apporter des résultats intéressants.

Le modèle du Chapitre 3 n'en est lui qu'à ses débuts et appelle de nombreuses améliorations et extensions. Tout d'abord, sous réserve de l'existence d'un équilibre, l'incorporation d'une fonction de demande avec élasticité non nulle permettrait d'étudier de manière plus rigoureuse les effets de congestion en faisant varier ou en annulant purement et simplement la convexité de la fonction de coût d'investissement. La variable duale associée à cette contrainte de demande pourrait ainsi plus rigoureusement être interprétée comme un prix de marché, et permettre une représentation rigoureuse de la décentralisation de l'équilibre.

L'application numérique au marché électrique européen appelle à la réalisation d'une étude de sensibilité. L'exploration des frontières de définition des paramètres de coût permettant d'avoir par exemple un plafond d'émission contraignant, ou encore l'influence des valeurs de convexité sur les différences de coût actualisé de l'électricité, permettraient d'améliorer grandement la compréhension de ces mécanismes et leur portée opérationnelle.

La formulation du modèle numérique sous forme duale permettrait de modéliser des politiques particulières et notamment de simuler les coûts de certaines contraintes en représentant de manière rigoureuse un équilibre de deuxième rang. Ainsi, l'utilisation directe de la variable duale de la fonction de demande permettrait d'imposer l'égalisation du coût marginal de développement au prix anticipé de l'électricité, et ainsi calculer le coût d'ignorer les effets de congestion. De la même manière ces contraintes de second rang pourraient utiliser le prix du carbone comme donnée.

Il serait également possible de coupler le modèle analytique existant à un modèle à la Hotelling, afin d'explorer les liens entre accumulation de capital consommant des ressources polluantes et épuisables, et l'épuisement des dites ressources. La formulation du prix des ressources, de l'électricité et du carbone sous différentes hypothèses de disponibilité et d'intensité en carbone des ressources pourrait livrer quelques surprises.

Ce modèle d'accumulation de capital avec inertie des investissements se prêterait également bien à une application dans des secteurs autres que l'électricité. La représentation d'un passage à un secteur des transports dominé par les véhicules électriques pourrait donner des éléments de discussion intéressants sur les politiques en cours dans le secteur. Le modèle pourrait également être appliqué à la question d'actualité du compromis entre rénovation rapide et superficielle vs. rénovation coûteuse mais en profondeur dans le secteur des bâtiments.

L'incorporation de myopie ou d'incertitude dans le modèle analytique ou numérique le cas échéant permettrait d'apporter un peu de réalisme à la représentation des politiques climat-énergie dans le secteur électrique, et éventuellement laisser la place à des actions du régulateur pour harmoniser les marchés.

Les Chapitres 3 et 4 se prêteraient enfin bien à une approche plus empirique, pour tester les hypothèses de convexité des coûts d'investissement ou bien la validité des hypothèses d'efficacité des instruments combinés par rapport à leurs performances théoriques des instruments pris isolément.

# COMPLEMENT TO CHAPTER 2

This complement aims at giving some additional elements of discussion compared to the published version of Chapter 2 (Lecuyer and Quirion 2013). It discusses some of the assumptions made in the chapter and possible implications for public policy.

## ASSUMPTIONS OF THE MODEL

### Linear marginal damages

Cumulative emissions have been found to be a good proxy for climate change (Allen et al. 2009, Matthews et al. 2009). In the case of climate change control, most researchers agree that the marginal damage curve of $CO_2$ emissions over a few years period is relatively flat because $CO_2$ is a stock pollutant (Newell and Pizer 2003).[14] Moreover, the model only consider a minor share of the worlds GHG emissions, considering only emissions from the European electricity sector (approx. 1.05 Gt$CO_2$ in Europe in 2008 (Trotignon and Delbosc 2008), compared to 20 Gt$CO_2$ for electricity production in the world in 2008 (IEA 2011), and 34.7 Gt$CO_2$ total emissions in 2008 Peters et al. (2012)). As a result, damages from this small share of emissions can be approximated as constant over a short period, e.g. for the sake of a schematic reasoning in a static model. Such an approximation may however not be valid for the world emissions, whose marginal damages are increasing. A dynamic model would therefore have to consider an (exogenously) increasing marginal level of damages, even for a small share of the world emissions.

### Stylized production technologies and linear marginal costs

The model represents two stylized technologies, one emitting (e.g. gas power plants in the numerical application), the other carbon free (e.g. renewables in the numerical model). The assumption of explicit and linear marginal cost functions allows keeping some mathematical tractability in the model and give some basic economic insight into complex market equilibriums involving the use of inverse functions. Using general forms for the cost function would result in less general results, because they would only apply to small changes around the equilibrium (as in Chapter 1).

The long term marginal cost functions used in this model take in a limited way capacity expansion costs into account. They do not represent capacity constraints however, nor the constraints of having fixed and stranded costs or bulky investment. Ignoring the partition of costs into fixed and variable costs leads to much simplification, but leaves aside important dynamic effects. In a dynamic framework with fixed and variable costs, MACs become

14. The possibility of catastrophic damages and of tipping points in climate change may however change the nature of the problem (Hallegatte et al. 2007, Weitzman 2009). The study of such events necessitates however specific modeling tools, and is out of the scope of this chapter.

much more difficult to determine, as discussed in Chapter 3, because they are implicit and endogenous functions.

This results in ignoring possible non-linear interactions between renewable and fossil technologies. The model ignores the decreased profitability of investments in one technology when the other expands, due to the decreasing operation time. Having an uncertain electricity demand in a dynamic model such as in Chapter 3 would lead to probably unexpected results on the use of one production technology over the other.

Having linear long term marginal costs allows for clarity in the analytical results, but implies an assumption of decreasing returns for electricity production in the long run. While it is not true at a local level, this assumption seems reasonable at a European level where all new production plants are small compared to the total installed capacity.

Other factors can influence long term production costs in a non-linear way, even in a static framework. For example, grid connection costs could induce much higher additional abatement costs when the share of renewables is high than when it is low. Some renewable investment may reduce connection costs (for local use for instance), other may increase them (when connecting a off-shore wind farms for instance) compared to the average connection costs of additional renewable capacity.

Intermittency effects would also have indeterminate effects at the European level. One the one hand, their impact on the production costs increase faster than the renewable market share, because of non-linear back-up needs. On the other hand, as renewables expand in zones with uncorrelated wind regimes, the intermittency may cancel out to some degree, decreasing such needs.

### Sources of uncertainty

The intuition behind the model applies when the uncertainty on marginal abatement costs leads to the possibility of a nil carbon price, as detailed in the first part of the chapter. This uncertainty on the MACs captures economic uncertainty, as well as uncertainty on the technological costs (Quirion 2005). In the analytical model, we assume only one source of uncertainty, namely uncertainty on the electricity demand, but other sources could be imagined, such as uncertainty on the learning factors of some immature carbon-free technologies, or on the environmental damages from emissions (see also the discussion above).

Uncertainty on the demand for allowances from sectors covered by the EU-ETS other than the electricity sector sectors could also influence the abatement costs, for a given level of emission cap. An excess of allowances has been however building up since the first EU-ETS period in these sectors, and this excess will probably last until 2020. Moreover, their level of activity is correlated to the demand of electricity, since the latter comes in part from industrial sectors. Adding the possibility of excess allowances from additional EU-ETS sectors would thus probably only further decrease the carbon price, and increase the risk that it drops to zero. In the sensitivity analysis of the numerical part of the chapter, we consider a range of values for this excess of allowances, and show that it contributes indeed to the risk of a nil carbon price.

## POSSIBLE IMPLICATIONS FOR PUBLIC POLICY

### Reforming the EU-ETS

Chapter 2 aims at discussing optimal policy choice in a context of uncertain demand for electricity, and in a second best situation where the regulator can only chose instruments in a limited set including an ETS and a subsidy for renewables. By doing this we assume that the regulator optimizes the welfare by setting the level of the instruments, and in particular, that the optimal emission cap may vary according to the level of uncertainty. In reality, the level of the EU-ETS (and of the renewable subsidies, see discussion in Chapter 4) also depends on political parameters, and has been fixed for the years to come.

The recent debate about back-loading or even removing some allowances, and therefore adjust the emission cap, fits well with the results of this chapter. The latter suggest that the benefits of adjusting the cap may depend on the level of uncertainty on abatement costs and electricity demand. As the level of uncertainty seems quite high for now (see discussion in the sensitivity analysis section), keeping renewable subsidies at a high enough level and combining them with the EU-ETS may increase the welfare.

### Choosing instruments for mitigation

The approach used in this chapter and the results obtained echo the now classic *Pigou vs. Coase* debate. The EU-ETS was an attempt to solve the problem of climate change through the proper definition of property rights on GHG emissions, with the underlying idea that it could have been less costly than the direct polluter-pays principle approach of taxing the externality. The possibility of a nil carbon price (due to the uncertainty on technological and economic factors in the electricity market, as well as to probable political factors, see Chapter 4 for a discussion) shows that initially, the balance of costs and benefits was indeed in favor of a property-right approach. Setting a tax at the level of the anticipated price resulting from the allowance market (from €30 to €10/t$CO_2$ as in the numerical application) would have resulted in more abatements, made at a higher average price than what is currently observed.

The aim of the chapter could therefore be questionable: why try to increase a carbon price by using an instrument that could be more costly? The assumption made in this chapter of a marginal environmental damage at the level of the initially anticipated price for EU-ETS allowances reflects more the level of ambition of the EU 2050 roadmap than of the current EU-ETS objectives. The underlying idea is that the uncertainties pertaining the EU-ETS may hinder the long term objective of reducing by at least 75 % the European GHG emissions, and that a corrective action may be necessary

### Implementing a renewable subsidy

The choice of a renewable subsidy to sustain the abatement effort and to supplement the expected carbon price should then be analyzed in relation to its actual social costs. The model assumes a perfect subsidy and only one renewable technology. In reality, the multiplicity of renewable technologies calls for a whole range of subsidies, for various reasons discussed in Chapter 4, with the temptation to "pick the winner" and further undermine the efficiency of the resulting carbon price. The level of the subsidies would then more reflect the lobbying resources spent than the actual positive externalities expected from those technologies.

Introducing inefficiency factors and additional costs for the renewable subsidy would obviously reduce its benefits. Except in situation where these inefficiencies would become prohibitively high, there should however still be situations justifying an additional instrument, especially since the social costs of the counter-factual scenario (an EU-ETS in isolation) increase if there is a possibility of a nil carbon price, since abatements are then reduced and the expected abatement effort then stays below the marginal damage from emissions. The benefice of such a policy combination would however be much more difficult to measure in practice.

### Alternative instruments

The instrument that could supplement the EU-ETS could be of various nature. The renewable subsidy considered in the chapter is only an example, and the same argument could be applied to other instruments, e.g. an instrument promoting energy efficiency, a tax on fossil fuels, or other. Floor prices have also been proposed as an instrument to ensure a minimum level of abatement. Such a floor price would be of a different nature than the instruments listed above however, and would not completely cancel the benefits of an additional renewable subsidy in case of high uncertainty, unless this floor price is equal or above the marginal damage value.

Renewable subsidies, feed-in tariffs and renewable quotas would all bring the additional abatements discussed in this chapter. Their relative characteristics regarding variability of renewable production and welfare effects would be an interesting avenue for further research.

### Opportunity cost of public funds

Results from the literature on environmental fiscality show clearly that a tax is better than an instrument neutral with respect to public funds, itself being better than a subsidy paid with public funds (as is the case here), because of the reduced distorsive effects induced by the additional taxes needed to finance this subsidy. The study of the optimal taxation of climate externalities and the possibility of double dividends would however best be studied in a general equilibrium model incorporating explicit taxes. As discussed above, one way of taking such costs into account would be to add a multiplicative factor on the cost of the subsidy, thereby decreasing the parameter range where adding a subsidy would improve the welfare.

## ADDITIONAL COMMENTS

The first part of the chapter, detailing the intuition behind the results in a graphical way, is based on the framework developed by Weitzman (1974). We took some liberties compared to his approach however for clarity. Weitzman compares marginal environmental benefits with marginal costs. When applied to climate change, this has however a negative nature that twists the equations and hinders a clear representation of the intuitions behind the results. For climate change, the marginal benefits described by Weitzman are indeed abatements, or negative emissions, and the marginal costs are the marginal abatement costs (MAC curves). It seemed more proper to speak of damages from emissions, and of abatement costs, instead of the reverse, and to represent the graphical intuition as a function of abatements instead of emissions.

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# A APPENDIX TO CHAPTER 1

## A.1 PROOF OF PROPOSITION 1.1

We totally differentiate the market clearing and first-order conditions (1.1-1.5):

$$dx = df + dr \tag{A.1}$$
$$d\Omega = df \tag{A.2}$$
$$d\phi = dp - \frac{df}{\sigma_f} \tag{A.3}$$
$$d\rho = \frac{dr}{\sigma_r} \tag{A.4}$$
$$de = -dx + \sigma_u dq \tag{A.5}$$
$$d\varepsilon = -\frac{de + dx}{\sigma_u} + \frac{de}{\sigma_e} \tag{A.6}$$
$$dt = d\alpha_r(\rho - p) + \alpha_r(d\rho - dp) \tag{A.7}$$
$$dq = dp + dt \tag{A.8}$$
$$dr = d\alpha_r(f + r) + \alpha_r(df + dr) \tag{A.9}$$

The slopes of the supply functions are denated $\sigma_i$. They correspond to the inverse of the derivatives of the marginal cost functions: $\sigma_f = \frac{1}{C_f''(f)} \geqslant 0$ ; $\sigma_r = \frac{1}{C_r''(r)} \geqslant 0$ ; $\sigma_e = \frac{1}{C_e''(e)} \geqslant 0$. We define $\sigma_u$ as the slope of the demand curve: $\sigma_u = \frac{1}{U''(x+e)} \leqslant 0$.[1]

Solving (A.1-A.9) gives an expression for the total derivatives of each endogenous variable (prices and quantities) as a sum of variations induced by each exogenous variable (the policy instruments) around the market equilibrium:

$$df = d\Omega \tag{A.10}$$
$$dr = d\rho\sigma_r \tag{A.11}$$
$$d\alpha_r = \frac{(1-\alpha_r)\alpha_r d\rho\sigma_r}{r} - \frac{\alpha_r^2 d\Omega}{r} \tag{A.12}$$
$$dx = d\rho\sigma_r + d\Omega \tag{A.13}$$
$$de = -d\rho\frac{\sigma_e\sigma_r}{\sigma_e - \sigma_u} - d\Omega\frac{\sigma_e}{\sigma_e - \sigma_u} - d\varepsilon\frac{\sigma_e\sigma_u}{\sigma_e - \sigma_u} \tag{A.14}$$
$$dq = -d\rho\frac{\sigma_r}{\sigma_e - \sigma_u} - \frac{d\Omega}{\sigma_e - \sigma_u} - d\varepsilon\frac{\sigma_e}{\sigma_e - \sigma_u} \tag{A.15}$$
$$\begin{aligned} dp = &-d\Omega\frac{\left(\alpha_r^2(p-\rho)(\sigma_e - \sigma_u) + r\right)}{(1-\alpha_r)r(\sigma_e - \sigma_u)} - d\varepsilon\frac{\sigma_e}{(1-\alpha_r)(\sigma_e - \sigma_u)} \\ &- d\rho\frac{((1-\alpha_r)\alpha_r\sigma_r(\rho - p)(\sigma_e - \sigma_u) + r(\alpha_r(\sigma_e - \sigma_u) + \sigma_r))}{(1-\alpha_r)r(\sigma_e - \sigma_u)} \end{aligned} \tag{A.16}$$

1. We drop the arguments of the second derivative functions. Note that the $\sigma_i$ are constant when assuming quadratic functions.

**Table A.1:** Signs of the partial derivatives and of the elasticity of substitution of market variables (total electricity production $(x)$, from fossil and renewables $(f, r)$, EE $(e)$, wholesale and retail price $(p, q)$, electricity consumption tax $(t)$ and carbon price $(\phi)$) with respect to policy variables (emission cap $(\Omega)$, EE subsidy $(\varepsilon)$ and FiT $(\rho)$) when the FiT is financed by consumers.

| | $dq$ | $dp$ | $dt$ | $d\phi$ |
|---|---|---|---|---|
| $d\Omega$ | $-$ | ? | ? | ? |
| $d\rho$ | $-$ | $-$ | $+$ | $-$ |
| $d\varepsilon$ | $-$ | $-$ | $+$ | $-$ |

*Intersection of line* $i$ *and column* $j$ *gives the sign of* $\frac{\partial j}{\partial i}$. *Table elements are positive* $(+)$, *negative* $(-)$, *nil* $(\cdot)$ *or indeterminate* $(?)$.

$$dt = d\rho \frac{\alpha_r((1-\alpha_r)\sigma_r(\rho - p)(\sigma_e - \sigma_u) + r(\sigma_e + \sigma_r - \sigma_u))}{(1-\alpha_r)r(\sigma_e - \sigma_u)} + d\Omega \frac{\alpha_r(\alpha_r(p-\rho)(\sigma_e - \sigma_u) + r)}{(1-\alpha_r)r(\sigma_e - \sigma_u)} + d\varepsilon \frac{\alpha_r \sigma_e}{(1-\alpha_r)(\sigma_e - \sigma_u)} \tag{A.17}$$

$$d\phi = -d\varepsilon \frac{\sigma_e}{(1-\alpha_r)(\sigma_e - \sigma_u)} - d\rho \frac{((1-\alpha_r)\alpha_r\sigma_r(\rho - p)(\sigma_e - \sigma_u) + r(\alpha_r(\sigma_e - \sigma_u) + \sigma_r))}{(1-\alpha_r)r(\sigma_e - \sigma_u)} + d\Omega \left( \frac{\alpha_r(\rho - p)}{(1-\alpha_r)x} - \frac{1}{(1-\alpha_r)(\sigma_e - \sigma_u)} - \frac{1}{\sigma_f} \right) \tag{A.18}$$

In each expression, the coefficient of $d\phi$, $d\rho$ and $d\varepsilon$ corresponds to the partial derivatives of the respective market variable (quantity or price) with respect to the corresponding policy variable ($\phi$, $\rho$ or $\varepsilon$). In (A.15), the coefficient of $d\rho$ is the variation of the retail price when the feed-in tariff (FiT) is changing, or the partial derivative of the retail price with respect to the FiT: $\frac{\partial q}{\partial \rho} = \frac{-\sigma_r}{\sigma_e - \sigma_u}$. This particular partial derivative is negative, meaning that increasing the FiT decreases the retail electricity price at equilibrium.

Correspondingly, the partial derivative of the consumption tax with respect to the FiT is positive, and the partial derivative of the wholesale price with respect to the FiT is negative, menaing that an increase in the FiT will result in an increase of the tax and a decrease of the wholesale electricity price.

## A.2 PROOF OF PROPOSITION 1.2

From (A.10-A.18), we deduce the signs of the partial derivatives of prices and the tax with respect to the various exogenous policy variables. The signs are gathered in Tab. A.1.[2]

The partial derivatives $\frac{\partial q}{\partial \rho}$ and $\frac{\partial q}{\partial \varepsilon}$; $\frac{\partial p}{\partial \rho}$ and $\frac{\partial p}{\partial \varepsilon}$; $\frac{\partial t}{\partial \rho}$ and $\frac{\partial t}{\partial \varepsilon}$; $\frac{\partial \phi}{\partial \rho}$ and $\frac{\partial \phi}{\partial \varepsilon}$ are respectively of the same sign. The effects of a simultaneous increase in the FiT $\rho$ and the energy efficiency subsidy $\varepsilon$ will therefore add up and be reinforcing.

2. Note that elasticities of substitution of endogenous market variables with respect to exogenous instruments are of the same sign as the respective partial derivatives, as all quantity or prices are positive.

From (A.13) and (A.14) we get the partial derivative of electricity production and energy savings with respect to the FiT and the subsidy:

$$\frac{\partial(x+e)}{\partial\rho} = \frac{\partial x}{\partial\rho} + \frac{\partial e}{\partial\rho} = \sigma_r - \frac{\sigma_e\sigma_r}{\sigma_e - \sigma_u} = \frac{-\sigma_r\sigma_u}{\sigma_e - \sigma_u} > 0$$
$$\frac{\partial(x+e)}{\partial\varepsilon} = \frac{\partial x}{\partial\varepsilon} + \frac{\partial e}{\partial\varepsilon} = -\frac{\sigma_e\sigma_u}{\sigma_e - \sigma_u} > 0$$
$$\frac{\partial e}{\partial\rho} = -\frac{\sigma_e\sigma_r}{\sigma_e - \sigma_u} < 0$$
$$\frac{\partial e}{\partial\varepsilon} = -\frac{\sigma_e\sigma_u}{\sigma_e - \sigma_u} > 0$$

Total energy service increases with the FiT and the subsidy, and efficiency investment increase with the subsidy but decrease with the FiT.

## A.3 PROOF OF PROPOSITION 1.3

Eq. (A.15) gives the expression of the changes in the consumer price when the cap varies:

$$\frac{\partial q}{\partial\Omega} = -\frac{1}{\sigma_e - \sigma_u} < 0 \tag{A.19}$$

It is negative.

Eq. (A.17) gives the expression of the changes in the consumer tax when the cap varies:

$$\frac{\partial t}{\partial\Omega} = \frac{\alpha_r}{1-\alpha_r}\left(\frac{1}{\sigma_e - \sigma_u} - \frac{\alpha_r(\rho - p)}{r}\right) \tag{A.20}$$

Tightening the cap decreases the total electricity production and increases the tax needed to finance an unchanged amount of renewables, proportionnaly to the level of the the FiT and the quantity of renwables (second term). It also increases the quantity of efficiency investment, which limits the consumer price decrease and hence tends to limit the need for a higher tax (first term). This effect is stronger when demand and energy efficiency supply functions are inelastic ($\sigma_e$ and $\sigma_u$ are small).

Changes in the cap have similar effects on the wholesale price, since it is equal to the difference between consumer price and tax (A.8).

Eq. (A.18) gives the partial derivative of the carbon price with respect to the emission cap:

$$\frac{\partial\phi}{\partial\Omega} = \frac{\alpha_r(\rho - p)}{(1-\alpha_r)x} - \frac{1}{(1-\alpha_r)(\sigma_e - \sigma_u)} - \frac{1}{\sigma_f} \tag{A.21}$$

In (A.21), we see that $\frac{\partial\phi}{\partial\Omega}$ is more likely to be negative when $\frac{\alpha_r(\rho-p)}{(1-\alpha_r)x}$ is small and $\frac{1}{(1-\alpha_r)(\sigma_e+\sigma_u)}$ and $\frac{1}{\sigma_f}$ are big. This happens when $\sigma_u, \sigma_e, \sigma_f$ are small (or in other terms, when supply and demand functions are inelastic), $x$ is big, $\alpha_r$ is small and the net subsidy $(\rho - p)$ is small.

## A.4 PROOF OF PROPOSITION 1.4

Totally differentiating (1.10) and incorporating (A.10-A.18) gives the expression of welfare changes as a function of the various policy variations (emission cap, FiT financed by consumers and an energy efficiency subsidy):

$$\begin{aligned} dW = {} & d\Omega \frac{((\phi-\delta)(\sigma_e-\sigma_u)+\alpha_r(\rho-p)(\sigma_e-\sigma_u)+\sigma_e\varepsilon)}{\sigma_e-\sigma_u} \\ & + d\rho \frac{\sigma_r(\sigma_e\varepsilon-(1-\alpha_r)(\rho-p)(\sigma_e-\sigma_u))}{\sigma_e-\sigma_u} + d\varepsilon \frac{\sigma_e\sigma_u\varepsilon}{\sigma_e-\sigma_u} \end{aligned} \tag{A.22}$$

Note that $\alpha_r(\Omega,\rho,\varepsilon) = \frac{C_r'^{-1}(\rho)}{C_r'^{-1}(\rho)+\Omega}$ and $\phi(\Omega,\rho,\varepsilon) = p - C_f'(\Omega)$ are both endogenous, and can be expressed as a function of the exogenous policy variables.

The optimum is found by solving the system $(\frac{\partial W}{\partial \phi}=0, \frac{\partial W}{\partial \rho}=0, \frac{\partial W}{\partial \varepsilon}=0)$ for $(\phi;\rho;\varepsilon)$, and by verifying the second-order conditions. We compute the Hessian matrix $\mathcal{H}$ of the welfare as a function of policy instruments (for simplicity we assume the third derivatives of the cost and utility function are nil):

$$\mathcal{H} = \begin{pmatrix} -\frac{2\alpha_r\varepsilon}{x^2}-\frac{1}{\sigma_f}-\frac{1}{\sigma_e-\sigma_u} & \frac{(1-2\alpha_r)\varepsilon\sigma_r}{x^2}-\frac{\sigma_r}{\sigma_e-\sigma_u} & 0 \\ \frac{(1-2\alpha_r)\varepsilon\sigma_r}{x^2}-\frac{\sigma_r}{\sigma_e-\sigma_u} & -\frac{2(1-\alpha_r)\varepsilon\sigma_r^2}{x^2}-\frac{\sigma_r^2}{\sigma_e-\sigma_u}-\sigma_r & 0 \\ 0 & 0 & \frac{\sigma_e\sigma_u}{\sigma_e-\sigma_u} \end{pmatrix} \tag{A.23}$$

The optimal cap is such that the carbon price equals the marginal damage, the optimal net subsidies to renewables and energy efficiency are nil, leading to a nil consumption tax so that retail and wholesale prices are equal. The eigenvalues of $\mathcal{H}$ are all negative at the optimum, which is therefore a maximum.

It is also possible to compute the total differentials of the profits and surpluses separatly:

$$d\Pi_f = d\Omega\frac{\Omega}{\sigma_f} \tag{A.24}$$

$$d\Pi_r = -d\rho\frac{\alpha_r\Omega}{\alpha_r-1} \tag{A.25}$$

$$\begin{aligned} d\bar{U} = {} & +d\Omega\frac{\Omega}{(1-\alpha_r)(\sigma_e-\sigma_u)} + d\rho\frac{\sigma_r\Omega}{(1-\alpha_r)(\sigma_e-\sigma_u)} \\ & + d\varepsilon\left(e+\frac{\sigma_e\Omega}{(1-\alpha_r)(\sigma_e-\sigma_u)}\right) \end{aligned} \tag{A.26}$$

Note that we assume that electricity producers pay for their emission costs, e.g. emission allowances are auctionned rather than grandfathered. They do not benefit from the carbon rent, corresponding to the total emissions times the value of carbon:

$$\begin{aligned} d\mathcal{R}_\phi &= d\,[f\cdot\phi] = df\cdot\phi + f\cdot d\phi \\ &= +d\Omega\cdot\Omega\left(\phi+\frac{\alpha_r(\rho-p)}{(1-\alpha_r)x}-\frac{1}{(1-\alpha_r)(\sigma_e-\sigma_u)}-\frac{1}{\sigma_f}\right) \\ &\quad - d\rho\frac{\Omega((1-\alpha_r)\alpha_r\sigma_r(\rho-p)(\sigma_e-\sigma_u)+r(\alpha_r(\sigma_e-\sigma_u)+\sigma_r))}{(1-\alpha_r)r(\sigma_e-\sigma_u)} \\ &\quad - d\varepsilon\frac{\sigma_e\Omega}{(1-\alpha_r)(\sigma_e-\sigma_u)} \end{aligned} \tag{A.27}$$

The sign of each partial derivative follows.

## A.5 CARBON RENT AS A FUNCTION OF THE CAP AND LAFFER CURVE

Eq. (A.27) gives us the partial derivative of the carbon rent with respect to the emission cap:

$$\frac{\partial \mathcal{R}_\phi}{\partial \Omega} = \left( \phi + \frac{\alpha_r(\rho - p)}{(1-\alpha_r)x} - \frac{1}{(1-\alpha_r)(\sigma_e - \sigma_u)} - \frac{1}{\sigma_f} \right) \tag{A.28}$$

When the cap gets small, the share of renewables tends to 1. Inversely, since we assume a binding cap, whe nthe cap gets big, the share of renewable tends to 0. We take the limit of the partial derivative described above:

$$\lim_{\substack{\Omega \to 0 \\ \alpha_r \to 1}} \frac{\partial \mathcal{R}_\phi}{\partial \Omega} = \phi > 0 \tag{A.29}$$

$$\lim_{\substack{\Omega \to \infty \\ \alpha_r \to 0}} \frac{\partial \mathcal{R}_\phi}{\partial \Omega} = -\infty < 0 \tag{A.30}$$

The equilibrium condition gives us the maximum of the carbon rent as a function of $\Omega$ (since the function is continuous and is increasing in zero, decreasing in $+\infty$ and has one unique extremum). Note that $\phi, \alpha_r, p, r$ are endogenous variables and depend on the policy variables.

$$\frac{\partial \mathcal{R}_\phi}{\partial \Omega} = 0 \tag{A.31}$$

$$\Rightarrow \Omega^\dagger = \frac{\phi}{\frac{1}{(1-\alpha_r)(\sigma_e-\sigma_u)} - \frac{\alpha_r^2(\rho-p)}{(1-\alpha_r)r} + \frac{1}{\sigma_f}} \tag{A.32}$$

# B APPENDIX TO CHAPTER 2

## B.1 PROOF OF PROPOSITION 2.3

We compute expected emissions in three instrument mix settings (see Appendix B.3 for a description of all instrument settings used and a reference to the expression of the complete solution):

- A **first-best instrument mix**, with a unique $CO_2$ price across all states of the world [1];
- A **second-best instrument mix**, with an European Union Emission Trading System (EU-ETS) and a renewable energy power (REP) subsidy;
- A **third-best instrument mix**, with an EU-ETS alone.

The uncertainty is assumed to be such as the $CO_2$ price resulting from an EU-ETS in the low-demand state turns out to be nil (as shown in the model description above). The expected emissions $\mathcal{E}_e$ are given by:

$$\mathcal{E}_e = \sum_{s \in \text{states}} \mathcal{P}_s \cdot (\tau \cdot f_s - a_s) \tag{B.1}$$

Let us call $\mathcal{E}_{e,X}$ the expected emissions for a given instrument mix $X \in [1,2,3]$, the index referring respectively to the first-best, second-best and third-best mix as described above:

$$\begin{aligned}
\mathcal{E}_{e,1} =& \iota_d \tau - \Delta(1-2\lambda)\tau + \iota_r \sigma_r \tau - \iota_f(\sigma_d + \sigma_r)\tau - \delta(1/(\sigma_a) \\
&+ (\sigma_d + \sigma_r)(\tau)^2) && \text{(B.2)}\\
\mathcal{E}_{e,2} =& \iota_d \tau - \Delta(1-2\lambda)\tau + \iota_r \sigma_r \tau - \iota_f(\sigma_d + \sigma_r)\tau && \text{(B.3)}\\
&- \frac{(\delta\sigma_a(\sigma_d + \sigma_r)(\lambda(\sigma_d - \sigma_r) + \sigma_r)(\tau)^4)}{(1 + \sigma_a(\sigma_d + \sigma_r - \lambda\sigma_r)(\tau)^2)} \\
&- \frac{(\delta(\lambda + \sigma_a(2\lambda\sigma_d + \sigma_r)(\tau)^2))}{(\sigma_a + (\sigma_a)^2(\sigma_d + \sigma_r - \lambda\sigma_r)(\tau)^2)} \\
\mathcal{E}_{e,3} =& \iota_d \tau - \Delta(1-2\lambda)\tau + \iota_r \sigma_r \tau - \iota_f(\sigma_d + \sigma_r)\tau && \text{(B.4)}\\
&- \delta\lambda(1/(\sigma_a) + (\sigma_d + \sigma_r)(\tau)^2)
\end{aligned}$$

where we see that $\mathcal{E}_{e,1} < \mathcal{E}_{e,2}$ and that $\mathcal{E}_{e,2} < \mathcal{E}_{e,3}$. This result can be linked to the differences i nthe expected carbon price.

$$\mathcal{C} = \sum_{s \in \text{states}} \mathcal{P}_s \cdot \phi_s \tag{B.5}$$

The expected carbon price for a given instrument mix $X \in [1,2,3]$ is:

$$\mathcal{C}_1 = \delta \tag{B.6}$$

$$\mathcal{C}_2 = \delta \cdot \frac{\lambda(1 + \sigma_a\sigma_d(\tau)^2)}{1 + \sigma_a(\sigma_d + \sigma_r - \lambda\sigma_r)\tau^2} \tag{B.7}$$

$$\mathcal{C}_3 = \lambda\delta \tag{B.8}$$

1. Since the marginal damage is flat, the first-best instrument is always a price instrument, e.g. a carbon tax.

with $\mathcal{C}_2 < \mathcal{C}_1$ and that $\mathcal{C}_2 < \mathcal{C}_3$.

## B.2 PROOF OF PROPOSITION 2.4

We solve the model by assuming only

$$\begin{cases} \tau \cdot f_+ - a_+ = \Omega \\ \phi_+ > 0 \end{cases}$$

and make no assumption about the level of emissions in the low-demand state. By using the method developed in Appendix B.5, we compute the difference of the emissions minus the cap:

$$(\tau \cdot f_- - a_-) - \Omega = -(\frac{(2\Delta\sigma_a(\sigma_d + (-1+\lambda)\sigma_r)(\tau)^3)}{(1+\sigma_a(\sigma_d+\sigma_r-\lambda\sigma_r)(\tau)^2))} + \frac{(\delta\sigma_a\sigma_d(\sigma_d+\sigma_r)(\tau)^4)}{(1+\sigma_a(\sigma_d+\sigma_r-\lambda\sigma_r)(\tau)^2)} + \frac{(\delta-2\Delta\sigma_a\tau+\delta\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)}{(\sigma_a+(\sigma_a)^2(\sigma_d+\sigma_r-\lambda\sigma_r)(\tau)^2)}$$

We then compute the partial derivative of this expression with respect to all parameters, and test their positivity.

## B.3 DESCRIPTION OF THE MODEL TYPES AND INSTRUMENT SETTINGS USED IN THE ANALYTICAL AND NUMERICAL RESULTS

| Label | Nature | Instrument setting | | | $\bar{P}_{CO_2}$ | See |
|---|---|---|---|---|---|---|
| | | Carbon tax | EU-ETS | REP Subsidy | | |
| $M_1$ | 1st Best | Yes | Useless | Useless | Positive | App. B.4 |
| $M_2^n$ | 2nd Best | Unavailable | Yes | Yes | Nil | App. B.5 |
| $M_2^p$ | 2nd Best | Unavailable | Yes | Yes | Positive | App. B.6 |
| $M_3^n$ | 3rd Best | Unavailable | Yes | Unavailable | Nil | App. B.7 |
| $M_3^p$ | 3rd Best | Unavailable | Yes | Unavailable | Positive | App. B.8 |

**Table B.1:** Description of the model solved in Appendix B and instrument settings

Table B.1 links the names used in the text and the instrument settings used in each case. The detailed description of the model framework and the optimal solution calculated using Mathematica are given in the subsequent Appendices. Calculation sheets are available upon request to the authors.

The model used for the analytical results differ slightly from the model used for the numerical results. The numerical model allows for allowance trading by adding an emitting sector from which the electricity producer can buy surplus allowances. The instruments settings and names attached are the same for both models.

Appendix B.4 to Appendix B.8 show the framework and optimal solution for the model used in the analytcal part. Appendix B.9 show the framework and optimal solution for the model used in the numerical part, with the $M_2^n$ setting. Showing the details of all settings for the model used in the numerical part would be very long and are not shown here. They are available upon request to the authors.

## B.4 FIRST BEST SETTING: MODEL WITH CARBON TAX

To simulate an economy-wide carbon tax, we add following constraint to the model framework from Section 2.3:

$$\phi_- = \phi_+$$

The socially optimal level of all market variables for the high-demand state (subscript +) and low demand (subscript –) are:

$$\begin{aligned}
\Omega^\star &= -(\frac{\delta}{\sigma_a}) + \Delta\tau + \iota_d\tau - \iota_f\sigma_d\tau - \iota_f\sigma_r\tau \\
&\quad + \iota_r\sigma_r\tau - \delta\sigma_d(\tau)^2 - \delta\sigma_r(\tau)^2 \\
\rho^\star &= 0 \\
f_-^\star &= -\Delta + \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d + \sigma_r) \\
&\quad - \delta(\sigma_d + \sigma_r)\tau \\
r_-^\star &= \sigma_r(\iota_f - \iota_r + \delta\tau) \\
p_-^\star &= \iota_f + \delta\tau \\
a_-^\star &= \frac{\delta}{\sigma_a} \\
\phi_-^\star &= \delta \\
f_+^\star &= \Delta + \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d + \sigma_r) \\
&\quad - \delta(\sigma_d + \sigma_r)\tau \\
r_+^\star &= \sigma_r(\iota_f - \iota_r + \delta\tau) \\
p_+^\star &= \iota_f + \delta\tau \\
a_+^\star &= \frac{\delta}{\sigma_a} \\
\phi_+^\star &= \delta
\end{aligned}$$

## B.5 SECOND BEST SETTING: MODEL WITH EU-ETS, REP SUBSIDY AND A NIL $CO_2$ PRICE IN THE LOW-DEMAND STATE

Solving the profit maximization problem of the producer gives the reaction functions of producers, depending on the level of policy instruments and the state of the world (the first-order conditions are given in (2.4-2.6)). Solving the welfare maximization problem of the social planner knowing all the reaction functions gives the following first-order conditions:

$$\left(\frac{\partial EW}{\partial \rho} = 0, \qquad \frac{\partial EW}{\partial \Omega} = 0\right) \qquad \Rightarrow$$

$$
\begin{aligned}
0 =& \frac{(\rho^\star \sigma_a \sigma_r (\sigma_d + \sigma_r - \lambda\sigma_r)(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\delta(-1+\lambda)\sigma_a\sigma_r(\sigma_d+\sigma_r)(\tau)^3)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
&+ \frac{(\sigma_r(\rho^\star + \delta(-1+\lambda)\tau))}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}
\end{aligned} \tag{B.9}
$$

$$
\begin{aligned}
0 =& \frac{(\iota_f \lambda \sigma_a(\sigma_d+\sigma_r)\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\lambda(\delta - (\Delta + \iota_d)\sigma_a\tau))}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
&+ \frac{(\lambda\sigma_a\tau(-\iota_r\sigma_r + \delta\sigma_d\tau))}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\lambda\sigma_a(\Omega^\star + \delta\sigma_r(\tau)^2))}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}
\end{aligned} \tag{B.10}
$$

from which we directly derive the optimal level of the policy instruments. By substituting the optimal levels of policy instruments in the reaction functions, we obtain the socially optimal level of all market variables for the high-demand state (subscript +) and low demand (subscript –).

The optimal solution is:

$$
\begin{aligned}
\Omega^\star &= -(\frac{\delta}{\sigma_a}) + \Delta\tau + \iota_d\tau - \iota_f\sigma_d\tau - \iota_f\sigma_r\tau + \iota_r\sigma_r\tau - \delta\sigma_d(\tau)^2 - \delta\sigma_r(\tau)^2 \\
\rho^\star &= -(\frac{(\delta\sigma_a(-\sigma_r + \lambda(\sigma_d+\sigma_r))(\tau)^3)}{(1+\sigma_a(\sigma_d+\lambda\sigma_r)(\tau)^2)}) - \frac{(\delta\tau(-(1/2) - \sigma_a\sigma_d(\tau)^2))}{(1+\sigma_a(\sigma_d+\lambda\sigma_r)(\tau)^2)} \\
f_-^\star &= -\Delta + \iota_d - \frac{(2(-\iota_r\sigma_r + \iota_f(\sigma_d+\sigma_r)))}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} + \frac{((\iota_f - \iota_r)\sigma_a(\sigma_r)^2(\tau)^2)}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{(2\sigma_a\sigma_d(\iota_f\sigma_d - \iota_r\sigma_r)(\tau)^2)}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\delta\sigma_a\sigma_r(\sigma_d+\sigma_r)(\tau)^3)}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{(\sigma_r\tau(\delta + 3\iota_f\sigma_a\sigma_d\tau))}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} \\
r_-^\star &= \frac{(2(\iota_f - \iota_r)\sigma_a\sigma_d\sigma_r(\tau)^2)}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} + \frac{((\iota_f - \iota_r)\sigma_a(\sigma_r)^2(\tau)^2)}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{(\delta\sigma_a\sigma_r(\sigma_d+\sigma_r)(\tau)^3)}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\sigma_r(2\iota_f - 2\iota_r + \delta\tau))}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} \\
p_-^\star &= \iota_f \\
a_-^\star &= 0 \\
\phi_-^\star &= 0 \\
f_+^\star &= \Delta + \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d+\sigma_r) - \delta(\sigma_d+\sigma_r)\tau - \frac{(\delta\sigma_r\tau)}{(2(1+\sigma_a(\sigma_d+\lambda\sigma_r)(\tau)^2))} \\
r_+^\star &= \frac{(2(\iota_f - \iota_r)\sigma_a\sigma_d\sigma_r(\tau)^2)}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} + \frac{((\iota_f - \iota_r)\sigma_a(\sigma_r)^2(\tau)^2)}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{(\delta\sigma_a\sigma_r(3\sigma_d+\sigma_r)(\tau)^3)}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\sigma_r(2\iota_f - 2\iota_r + 3\delta\tau))}{(2+\sigma_a(2\sigma_d+\sigma_r)(\tau)^2)} \\
p_+^\star &= \frac{(\sigma_a(\tau)^2(\iota_f\lambda\sigma_r + \delta\sigma_d\tau))}{(1+\sigma_a(\sigma_d+\lambda\sigma_r)(\tau)^2)} + \frac{(\iota_f + \delta\tau + \iota_f\sigma_a\sigma_d(\tau)^2)}{(1+\sigma_a(\sigma_d+\lambda\sigma_r)(\tau)^2)} \\
a_+^\star &= \frac{(\delta + \delta\sigma_a\sigma_d(\tau)^2)}{(\sigma_a + (\sigma_a)^2(\sigma_d+\lambda\sigma_r)(\tau)^2)} \\
\phi_+^\star &= \frac{(\delta + \delta\sigma_a\sigma_d(\tau)^2)}{(1+\sigma_a(\sigma_d+\lambda\sigma_r)(\tau)^2)}
\end{aligned}
$$

## B.6 SECOND BEST SETTING: MODEL WITH EU-ETS, REP SUBSIDY AND A STRICTLY POSITIVE $CO_2$ PRICE IN THE LOW-DEMAND STATE

We assumed through this paper that the carbon price is nil in the low-demand state of the world. This is the case for certain parameter combinations, as discussed in section 2.3.4. For some other combinations, the carbon price remains positive in both states, and the model is changed as follows. Equation (2.3) becomes:

$$\begin{cases} \tau \cdot f_- - a_- = \Omega \\ \phi_- > 0 \end{cases} \quad \text{or} \quad \begin{cases} \tau \cdot f_+ - a_+ = \Omega \\ \phi_+ > 0 \end{cases}$$

The optimal solution changes also and becomes:

$$\begin{aligned}
\Omega^\star &= -(\frac{\delta}{\sigma_a}) + \iota_d\tau - \iota_f\sigma_d\tau \\
&\quad - \iota_f\sigma_r\tau + \iota_r\sigma_r\tau - \delta\sigma_d(\tau)^2 - \delta\sigma_r(\tau)^2 \\
\rho^\star &= 0 \\
f_-^\star &= \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d+\sigma_r) - \delta(\sigma_d+\sigma_r)\tau - \frac{(\Delta)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
r_-^\star &= -(\frac{(\Delta\sigma_a\sigma_r(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2))} + \frac{((\iota_f-\iota_r)\sigma_a\sigma_d\sigma_r(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{((\iota_f-\iota_r)\sigma_a(\sigma_r)^2(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\delta\sigma_a\sigma_r(\sigma_d+\sigma_r)(\tau)^3)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{(\sigma_r(\iota_f-\iota_r+\delta\tau))}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
p_-^\star &= \frac{(\sigma_a(-\Delta+\iota_f(\sigma_d+\sigma_r))(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\delta\sigma_a(\sigma_d+\sigma_r)(\tau)^3)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{(\iota_f+\delta\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
a_-^\star &= \frac{\delta}{\sigma_a} - \frac{(\Delta\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
\phi_-^\star &= \delta - \frac{(\Delta\sigma_a\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
f_+^\star &= \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d+\sigma_r) - \delta(\sigma_d+\sigma_r)\tau + \frac{(\Delta)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
r_+^\star &= -(\frac{(\iota_r\sigma_a\sigma_d\sigma_r(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2))} + \frac{(\sigma_a(\Delta+\iota_f\sigma_d)\sigma_r(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{((\iota_f-\iota_r)\sigma_a(\sigma_r)^2(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\delta\sigma_a\sigma_r(\sigma_d+\sigma_r)(\tau)^3)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{(\sigma_r(\iota_f-\iota_r+\delta\tau))}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
p_+^\star &= \frac{(\sigma_a(\Delta+\iota_f\sigma_d)(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\iota_f+\delta\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{(\sigma_a(\tau)^2(\iota_f\sigma_r+\delta(\sigma_d+\sigma_r)\tau))}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}
\end{aligned}$$

$$
\begin{aligned}
a_+^\star &= \frac{\delta}{\sigma_a} + \frac{(\Delta\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} \\
\phi_+^\star &= \delta + \frac{(\Delta\sigma_a\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}
\end{aligned}
$$

## B.7 THIRD BEST SETTING: MODEL WITH EU-ETS ONLY AND A NIL $CO_2$ PRICE IN THE LOW-DEMAND STATE

To simulate a third-best setting with no REP subsidy, we add following constraint to the model framework from Section 2.3:

$$\rho = 0$$

The socially optimal level of all market variables for the high-demand state (subscript +) and low demand (subscript –) are:

$$
\begin{aligned}
\Omega^\star &= -(\frac{\delta}{\sigma_a}) + \Delta\tau + \iota_d\tau - \iota_f\sigma_d\tau - \iota_f\sigma_r\tau \\
&\quad + \iota_r\sigma_r\tau - \delta\sigma_d(\tau)^2 - \delta\sigma_r(\tau)^2 \\
\rho^\star &= 0 \\
f_-^\star &= -\Delta + \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d+\sigma_r) \\
r_-^\star &= (\iota_f - \iota_r)\sigma_r \\
p_-^\star &= \iota_f \\
a_-^\star &= 0 \\
\phi_-^\star &= 0 \\
f_+^\star &= \Delta + \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d+\sigma_r) - \delta(\sigma_d+\sigma_r)\tau \\
r_+^\star &= \sigma_r(\iota_f - \iota_r + \delta\tau) \\
p_+^\star &= \iota_f + \delta\tau \\
a_+^\star &= \frac{\delta}{\sigma_a} \\
\phi_+^\star &= \delta
\end{aligned}
$$

## B.8 THIRD BEST SETTING: MODEL WITH EU-ETS ONLY AND A POSITIVE $CO_2$ PRICE IN THE LOW-DEMAND STATE

To simulate a third-best setting with no REP subsidy, we add following constraint to the model framework from Appendix B.6:

$$\rho = 0$$

The socially optimal level of all market variables for the high-demand state (subscript +) and low demand (subscript –) are:

$$
\begin{aligned}
\Omega^\star &= -(\frac{\delta}{\sigma_a}) + \iota_d\tau - \iota_f\sigma_d\tau - \iota_f\sigma_r\tau \\
&\quad + \iota_r\sigma_r\tau - \delta\sigma_d(\tau)^2 - \delta\sigma_r(\tau)^2
\end{aligned}
$$

$$\rho^\star = 0$$

$$f_-^\star = \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d+\sigma_r) - \delta(\sigma_d+\sigma_r)\tau - \frac{(\Delta)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

$$r_-^\star = \frac{(\sigma_a(-\Delta+(\iota_f-\iota_r)\sigma_d)\sigma_r(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{((\iota_f-\iota_r)\sigma_a(\sigma_r)^2(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\delta\sigma_a\sigma_r(\sigma_d+\sigma_r)(\tau)^3)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\sigma_r(\iota_f-\iota_r+\delta\tau))}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

$$p_-^\star = \frac{(\sigma_a(-\Delta+\iota_f(\sigma_d+\sigma_r))(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\delta\sigma_a(\sigma_d+\sigma_r)(\tau)^3)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\iota_f+\delta\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

$$a_-^\star = \frac{\delta}{\sigma_a} - \frac{(\Delta\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

$$\phi_-^\star = \delta - \frac{(\Delta\sigma_a\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

$$f_+^\star = \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d+\sigma_r) - \delta(\sigma_d+\sigma_r)\tau + \frac{(\Delta)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

$$r_+^\star = \frac{(\Delta\sigma_a\sigma_r(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{((\iota_f-\iota_r)\sigma_a\sigma_r(\sigma_d+\sigma_r)(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\delta\sigma_a\sigma_r(\sigma_d+\sigma_r)(\tau)^3)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\sigma_r(\iota_f-\iota_r+\delta\tau))}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

$$p_+^\star = \frac{(\Delta\sigma_a(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\iota_f\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\delta\sigma_a(\sigma_d+\sigma_r)(\tau)^3)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)} + \frac{(\iota_f+\delta\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

$$a_+^\star = \frac{\delta}{\sigma_a} + \frac{(\Delta\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

$$\phi_+^\star = \delta + \frac{(\Delta\sigma_a\tau)}{(1+\sigma_a(\sigma_d+\sigma_r)(\tau)^2)}$$

## B.9 MODEL WITH ALLOWANCES FROM NON-ELECTRICITY EU-ETS SECTORS AND NIL $CO_2$ PRICE IN THE LOW-DEMAND STATE

Section 2.4 extends the model and allows for allowance trading by adding an emitting sector from which the electricity producer can buy surplus allowances. This surplus is labeled $e$ and its supply is modeled by a linear mac curve. The profit maximization problem becomes:

$$\begin{aligned}\max_{f,r,a,e} \Pi(p,f,r,a,e,\phi) &= p\cdot f + (p+\rho)\cdot r \\ &\quad - C_f(f) - C_r(r) - AC(a) \\ &\quad - AC_e(e) - PC_e(f,a,e,\phi)\end{aligned}$$

with

$$AC_e(e) = \frac{\sigma_e}{2}e^2 - \begin{cases}\iota_e\cdot e & \text{low demand}\\ 0 & \text{high demand}\end{cases}$$

The allowance purchasing cost is modified as follows:

$$PC_e(f, a, e, \phi) = \phi \cdot (\tau \cdot f - a + e)$$

and (2.3) becomes:

$$\begin{cases} \tau \cdot f_-^\star - a_-^\star < \Omega - e_-^\star \\ \phi_-^\star = 0 \end{cases}$$

$$\text{or} \qquad \begin{cases} \tau \cdot f_+^\star - a_+^\star = \Omega - e_+^\star \\ \phi_+^\star > 0 \end{cases}$$

The welfare maximization problem becomes:

$$\begin{aligned} \max_{\Omega,\rho} EW(\Omega, \rho) = \sum_{\text{states}} \frac{1}{2}[CS(p) \\ + \Pi(p, f, r, a, e, \phi) - dam_e(f, a, e) \\ - \rho \cdot r + PC_e(f, a, e, \phi)] \end{aligned}$$

where $dam_e(\cdot)$ is the modified environmental damage function:

$$dam_e(f, a, e) = \delta \cdot (\tau f - a - e)$$

The optimal solution of this problem is the following:

$$\begin{aligned} \Omega^\star &= -(\frac{(\delta(\sigma_a + \sigma_e))}{(\sigma_a \sigma_e)}) \\ &\quad + (\Delta + \iota_d + \iota_r \sigma_r - \iota_f(\sigma_d + \sigma_r))\tau \\ &\quad - \delta(\sigma_d + \sigma_r)(\tau)^2 \\ \rho^\star &= \frac{(\delta\tau(\sigma_a + \sigma_e + \sigma_a\sigma_e(\sigma_d + \sigma_r)(\tau)^2))}{(2(\sigma_a + \sigma_e) + \sigma_a\sigma_e(2\sigma_d + \sigma_r)(\tau)^2)} \\ f_-^\star &= -\Delta + \iota_d - \iota_f\sigma_d - \iota_f\sigma_r \\ &\quad + \iota_r\sigma_r - \frac{(\delta\sigma_r(\sigma_d + \sigma_r)\tau)}{(2\sigma_d + \sigma_r)} \\ &+ \frac{(\delta(\sigma_a + \sigma_e)(\sigma_r)^2\tau)}{(2\sigma_d + \sigma_r)(2(\sigma_a + \sigma_e) + \sigma_a\sigma_e(2\sigma_d + \sigma_r)(\tau)^2)} \\ r_-^\star &= \frac{((\iota_f - \iota_r)\sigma_a\sigma_e\sigma_r(2\sigma_d + \sigma_r)(\tau)^2)}{(2(\sigma_a + \sigma_e) + \sigma_a\sigma_e(2\sigma_d + \sigma_r)(\tau)^2)} \\ &\quad + \frac{(\delta\sigma_a\sigma_e\sigma_r(\sigma_d + \sigma_r)(\tau)^3)}{(2(\sigma_a + \sigma_e) + \sigma_a\sigma_e(2\sigma_d + \sigma_r)(\tau)^2)} \\ &\quad + \frac{((\sigma_a + \sigma_e)\sigma_r(2\iota_f - 2\iota_r + \delta\tau))}{(2\sigma_e + \sigma_a(2 + 2\sigma_d\sigma_e(\tau)^2 + \sigma_e\sigma_r(\tau)^2))} \\ p_-^\star &= \iota_f \\ a_-^\star &= 0 \\ e_-^\star &= \frac{(\iota_e)}{(\sigma_e)} \\ \phi_-^\star &= 0 \\ f_+^\star &= \Delta + \iota_d + \iota_r\sigma_r - \iota_f(\sigma_d + \sigma_r) - \delta(\sigma_d + \sigma_r)\tau \\ &\quad - \frac{(\delta(\sigma_a + \sigma_e)\sigma_r\tau)}{(2(\sigma_a + \sigma_e) + \sigma_a\sigma_e(2\sigma_d + \sigma_r)(\tau)^2)} \end{aligned}$$

$$\begin{aligned}
r_+^\star &= \frac{(\delta\sigma_a\sigma_e\sigma_r(3\sigma_d+\sigma_r)(\tau)^3)}{(2(\sigma_a+\sigma_e)+\sigma_a\sigma_e(2\sigma_d+\sigma_r)(\tau)^2)} + \sigma_r(\iota_f-\iota_r) \\
&\quad + \sigma_r\frac{(3\delta(\sigma_a+\sigma_e)\tau)}{(2(\sigma_a+\sigma_e)+\sigma_a\sigma_e(2\sigma_d+\sigma_r)(\tau)^2)} \\
p_+^\star &= \iota_f + \frac{(2\delta(\sigma_a+\sigma_e)\tau)}{(2(\sigma_a+\sigma_e)+\sigma_a\sigma_e(2\sigma_d+\sigma_r)(\tau)^2)} \\
&\quad + \frac{(2\delta\sigma_a\sigma_d\sigma_e(\tau)^3)}{(2(\sigma_a+\sigma_e)+\sigma_a\sigma_e(2\sigma_d+\sigma_r)(\tau)^2)} \\
a_+^\star &= \frac{(2\delta(\sigma_a+\sigma_e+\sigma_a\sigma_d\sigma_e(\tau)^2))}{(\sigma_a(2(\sigma_a+\sigma_e)+\sigma_a\sigma_e(2\sigma_d+\sigma_r)(\tau)^2))} \\
e_+^\star &= \frac{(2\delta(\sigma_a+\sigma_e+\sigma_a\sigma_d\sigma_e(\tau)^2))}{(\sigma_e(2(\sigma_a+\sigma_e)+\sigma_a\sigma_e(2\sigma_d+\sigma_r)(\tau)^2))} \\
\phi_+^\star &= \frac{(2\delta(\sigma_a+\sigma_e+\sigma_a\sigma_d\sigma_e(\tau)^2))}{(2(\sigma_a+\sigma_e)+\sigma_a\sigma_e(2\sigma_d+\sigma_r)(\tau)^2)}
\end{aligned}$$

# C APPENDIX TO CHAPTER 3

## C.1 DETAILS ON THE MARGINAL IMPLICIT RENTAL COST OF CAPITAL

Following Jorgenson (1967, p143),

$$e^{-\delta(\theta-t)}d\theta$$

is the flow of output produced during the time interval $[\theta, \theta+d\theta]$ by the marginal capacity built at time $t$ (taking into account the depreciation). If the capacity is built to be rented out at price $p_{i,t}$, then

$$e^{-rt}p_{i,t}\, e^{-\delta(\theta-t)}d\theta$$

is the discounted cash flow during this interval. The cost of the marginal capacity built at $t$ is

$$e^{-rt}c_i'(x_{i,t})$$

The value of this marginal investment is equal the discounted value of all the output produced by this unit of investment from $t$ to $\infty$:

$$e^{-rt}c_i'(x_{i,t}) = \int_t^\infty e^{-rt}p_{i,t}\, e^{-\delta(\theta-t)}d\theta$$

which simplifies into

$$c_i'(x_{i,t}) = \int_t^\infty p_{i,t}\, e^{-(\delta+r)(\theta-t)}d\theta$$

Differentiating the marginal investment cost with respect to time gives:

$$\frac{d}{dt}c_i'(x_{i,t}) = (\delta+r)c_i'(x_{i,t}) - p_{i,t}$$

allowing to express the implicit marginal rental cost of the capital:

$$p_{i,t} = (\delta+r)c_i'(x_{i,t}) - \frac{d}{dt}c_i'(x_{i,t})$$

## C.2 FIRST-ORDER CONDITIONS AND COMPLEMENTARITY SLACKNESS CONDITIONS

Before presenting simplified and easy-to-understand first order conditions at the next subsection, we methodically write the Hamiltonian, full FOCs and complementary slackness conditions. [1]

1. The transversality condition is replaced by the terminal condition that at some point the atmospheric carbon reaches its ceiling (3.7).

The Hamiltonian reads:

$$\begin{aligned}\mathcal{H} = e^{-rt} \sum_i c_i(x_{i,t}) + \alpha_i \cdot q_{i,t} + \sum_i \nu_{i,t}\,(x_{i,t} - \delta\, k_{i,t}) + \mu_t \sum_i R_i\, q_{i,t} \\ + \eta_t\,(m_t - \bar{M}) + \omega_t \left(D - \sum_i q_{i,t}\right) + \sum_i \gamma_{i,t}\,(q_{i,t} - k_{i,t}) \\ - \sum_i \lambda_{i,t}\, q_{i,t} - \sum_i \xi_{i,t}\, x_{i,t}\end{aligned} \tag{C.1}$$

The first-order conditions are:

$$\frac{\partial \mathcal{H}}{\partial x_i} = 0 \iff c_i'(x_{i,t}) = e^{rt}(-\nu_{i,t} + \xi_{i,t}) \tag{C.2}$$

$$\frac{\partial \mathcal{H}}{\partial q_i} = 0 \iff \gamma_{i,t} = \lambda_{i,t} - \mu_t R_i - \alpha_{i,t} + \omega_t \tag{C.3}$$

$$\dot{\nu}_{i,t} + \frac{\partial \mathcal{H}}{\partial k_i} = 0 \iff \dot{\nu}_{i,t} - \delta\nu_{i,t} = \gamma_{i,t} \tag{C.4}$$

$$\dot{\mu}_t + \frac{\partial \mathcal{H}}{\partial m_t} = 0 \iff \dot{\mu}_t = -\eta_t \tag{C.5}$$

The complementary slackness conditions are:

$$\forall i, t, \quad \xi_{i,t} \geqslant 0, \quad x_{i,t} \geqslant 0 \quad \text{and} \quad \xi_{i,t}\, x_{i,t} = 0 \tag{C.6}$$

$$\forall i, t, \quad \lambda_{i,t} \geqslant 0, \quad q_{i,t} \geqslant 0 \quad \text{and} \quad \lambda_{i,t}\, q_{i,t} = 0 \tag{C.7}$$

$$\forall i, t, \quad \eta_t \geqslant 0, \quad \bar{M} - m_t \geqslant 0 \quad \text{and} \quad \eta_t\,\left(\bar{M} - m_t\right) = 0 \tag{C.8}$$

$$\forall i, t, \quad \gamma_{i,t} \geqslant 0, \quad k_{i,t} - q_{i,t} \geqslant 0 \quad \text{and} \quad \gamma_{i,t}\,(k_{i,t} - q_{i,t}) = 0 \tag{C.9}$$

$$\forall t, \quad \omega_t \geqslant 0, \quad D - \sum_i q_{i,t} = 0 \quad \text{and} \quad \omega_t \left(D - \sum_i q_{i,t}\right) = 0 \tag{C.10}$$

## C.3 LEVELIZED COSTS IN A STATIC FRAMEWORK

Let us define an archetypal static model of electricity supply and demand, inspired by the handbook on energy economics by **?**. Producers minimize production $q_i^j$ and capacity $k_i$ costs over a set of technologies $i$ and over periods $j$, subject to a capacity constraint (capacity is equal or greater than production) and a demand constraint in MW:

$$\min_{k,q} \sum_{i,j} c_i \cdot k_i + \tau_j \cdot \alpha_i \cdot q_{i,j} \tag{C.11}$$

$$\begin{aligned} \text{s.t.} \ \forall (i,j) \quad & 0 \leqslant k_i - q_{i,j} && (\lambda_{i,j}) \\ \forall j \quad & 0 \leqslant \sum_i q_{i,j} - d_j && (\omega_j) \end{aligned}$$

Where $c_i$ are the unitary capacity costs (in \$/ MW), $\alpha_i$ are the unitary production costs (in \$/MWh), $\tau^j$ is the duration of period $j$ (in h), $\lambda_i^j$ and $\omega_j$ are respectively the dual variable associated to the capacity and the demand constraints, and can be interpreted as the capacity rent and the electricity price.

The Lagrangian reads:

$$\text{Lag} = \sum_{i,j} c_i \cdot k_i + \tau_j \cdot \alpha_i \cdot q_{i,j} - \sum_{i,j} \lambda_{i,j}(k_i - q_{i,j}) - \omega_j \sum_i q_{i,j} - d_j \tag{C.12}$$

The first order conditions give:

$$\tau_j \cdot \alpha_i + \lambda_{i,j} = \omega_j \tag{C.13}$$

$$c_i = \sum_j \lambda_{i,j} \tag{C.14}$$

Levelized costs are defined for each technology as the sum of capacity and production costs over all periods, divided by total production:

$$\text{LCOE}_i = \frac{c_i k_i + \sum_j \tau_j \alpha_i q_{i,j}}{\sum_j \tau_j q_{i,j}} \tag{C.15}$$

Subsituting with (C.14), and assuming a constant production rate (i.e. the capacity constraint is always binding):

$$\text{LCOE}_i = \frac{\sum_j \lambda_{i,j} + \tau_j \alpha_i}{\sum_j \tau_j} \tag{C.16}$$

Using (C.13), we get an expression for the levelized cost:

$$\text{LCOE}_i = \frac{\sum_j \omega_j}{\sum_j \tau_j} \tag{C.17}$$

LCOEs are equal to the average electricity price over all periods, and are independant for all production technologies.

## C.4 INVESTMENT PHASES AND ELECTRICITY PRICE

The number of inequalities combinations captured by the slackness conditions is large. The different cases may be tackled analytically if we assume that on the optimal path, the system passes through phases (this assumption is confirmed by numerical simulations with standard functional forms, but cannot be proved for general functions).

CARBON BUDGET CONSTRAINT Let $T_{air}$ be the date when the ceiling on atmospheric carbon is reached. Before $T_{air}$, the social cost of carbon $\mu_t$ is constant (C.5,C.8):

$$\forall t < T_{air}, \quad \mu_t = \mu > 0 \tag{C.18}$$

The carbon-free atmosphere can be seen as a non renewable resource depleted by GHG emissions. In this context, the optimal current carbon price $\mu e^{rt}$ follows the Hotelling's rule, i.e. grows at the discount rate, as abatement realized at any time contributes equally to meet the carbon budget. The carbon price $\mu$ is strictly positive as we focus on the case where the carbon budget is binding.

STEADY STATE Let $T$ be the date when the system reaches a steady state. During the steady state, the ZCT produces all the output. Indeed, atmospheric carbon is stable, hence emissions from the HCT and LCT must be nil (3.3,3.5):

$$\forall t \geqslant T,\ \dot{m}_t = 0 \implies q_{\ell,t} = q_{h,t} = 0 \tag{C.19}$$

HCT production can stop before the system reaches a steady state.

PHASING OUT THE HCT Let $T_\omega \leqslant T$ be the date when high-carbon production stops.

$$\forall t \geqslant T_\omega,\ q_{h,t} = 0 \tag{C.20}$$

LEMMA C.1. Before the HCT is phased out, the optimal output price $\omega_t$ is equal to the sum of variable cost and emission costs from the high-carbon technology:

$$\forall t \leqslant T_\omega, \quad \omega_t = \mu R_h + \alpha_h \tag{C.21}$$

*Proof.* By assumption, the HCT capacity is always underused ($q_{h,t} < k_{h,t}$), hence the multiplier associated with the capacity constraint is nil $\gamma_{h,t} = 0$ (C.9). While $h$ is used to produce the output, the multiplier associated with the positivity constraint is also nil $\lambda_{h,t} = 0$ (C.7). The output price $\omega_t$ can then be obtained from (C.3). □

In the power sector, Lemma C.1 means that as long as the marginal power plant is a coal power plant, the price of electricity is the cost of coal plus the carbon price times the emission rate of coal.

UNDERUSED LCT CAPACITY It is possible that at one point, production from the LCT declines. One possible reason is if fossil deposit are almost depleted. Another reason relates to GHG emissions. From $T_\omega$, the demand constraint (3.5) makes it impossible to reduce further emissions by using either additional $\ell$ or $z$. Total emissions can be reduced further by producing more with the ZCT and less with the LCT (since $R_z < R_\ell$). Therefore, from $T_\omega$ on, LCT production may decline to allow for more ZCT production. In particular, it may become beneficial to use less $\ell$ than allowed by installed capacities.

Let $T_\gamma \leqslant T_{air}$ be the date when LCT production is lower than its capacity:

$$\forall t \geqslant T_\gamma,\ q_{\ell,t} < k_{\ell,t} \tag{C.22}$$

LEMMA C.2. Along the optimal path, when low-carbon capacities are used, but under full capacity, variable costs from LCT determine the output price:

$$\forall t \in [T_\gamma, T] \quad \omega_t = \mu R_\ell + \alpha_\ell \tag{C.23}$$

*Proof.* The proof is similar to that of Lemma C.1. □

In general, the output price cannot be equal to the variable costs of both the HCT and the LCT (i.e. both Lemma C.1 and Lemma C.2 cannot hold at the same time). For instance, in the power sector, the marginal power plant may be coal or gas, but not both at the same time. [2] As a result, along the optimal path, the low-carbon capacities may not be underused before high-carbon production is phased out.

$$T_\gamma > T_\omega \tag{C.24}$$

2. We disregard the case where fuel costs compensate exactly differences in carbon intensities $\alpha_\ell - \alpha_h = \mu\,(R_h - R_\ell)$ as it requires a very restrictive set of assumptions.

LEMMA C.3. In the steady state, the output price equals the rental cost of the zero-carbon capacity:

$$\forall t \geqslant T \quad e^{rt}\omega_t = p_{z,t} \tag{C.25}$$

*Proof.* From (3.15), as the zero-carbon technology does not require to burn any resource ($\alpha_z = 0$), nor pay for any emission ($R_z = 0$). □

In the power sector, Lemma C.3 means that when all the electricity is produced from windmills, the market price of electricity equals the rental price of windmills.

STARTING AND ENDING DATES OF INVESTMENT Let $T_i$ be the date when investment in capacity $i$ starts. Let $T_\ell^e$ be the date when investment in the LCT ends.[3] The HCT is phased out only after investment in one of the green technologies started:

$$T_\omega \geqslant \min(T_\ell, T_z) \tag{C.26}$$

If the low-carbon capacity is underused, investment in new low-carbon capacity is not optimal. Therefore the latter stops before LCT production drops below installed capacity:

$$T_\ell^e \leqslant T_\gamma \tag{C.27}$$

ZCT investment starts before LCT investment ends:

$$T_z \leqslant T_\ell^e \tag{C.28}$$

At any given time, existing capacities are used in the merit order, i.e. capacities with the lowest variable cost are used first. This means that LCT production is never replaced by HCT production (3.9), or in other terms total instantaneous emissions never increase.

If LCT investment stops before investment in the ZCT starts, i.e. before ZCT production starts replacing HCT and LCT production, LCT production necessarily decreases at least with the depreciation rate of LCT capacity, and hence is replaced by HCT production to comply with the demand constraint, which is in contradiction with the previous statement.

## C.5 SOLVING FOR OPTIMAL MICS

We use the generic algorithm to solve the following first-order linear differential equation:

$$\frac{d}{dt}c_i'(x_{i,t}) = (\delta + r)\, c_i'(x_{i,t}) - e^{rt}\ (\omega_t - \mu\, R_i - \alpha_i\ ) \tag{C.29}$$

The general theory[4] ensures that if $z_{i,t}$ satisfies:

$$\dot{z}_{i,t} = -e^{-(\delta+r)t}\ \left(e^{rt}\,(\omega_t - \mu\, R_i - \alpha_i\ )\right) \tag{C.30}$$

3. We do not need an equivalent definition for the ZCT as it used in the steady state and investment never stop.

4. See for instance **?**

Then $c_i'(x_{i,t}) = e^{(\delta+r)t} z_{i,t}$ is a solution of (C.29). The general solution of (C.30) on an interval $(\sigma_i, \tau_i)$ reads:

$$z_{i,t} = z_{i,\tau_i} + \int_t^{\tau_i} e^{-(\delta+r)\theta} e^{r\theta} (\omega_\theta - \mu R_i - \alpha_i \,) \, d\theta \tag{C.31}$$

Leading to:

$$c_i'(x_{i,t}) = e^{(\delta+r)t} z_{i,\tau_i} + e^{(\delta+r)t} \int_t^{\tau_i} e^{-(\delta+r)\theta} e^{r\theta} (\omega_\theta - \mu R_i - \alpha_i \,) \, d\theta \tag{C.32}$$

$$= e^{(\delta+r)t} z_{i,\tau_i} + e^{rt} \int_t^{\tau_i} e^{-\delta(t-\theta)} (\omega_\theta - \mu R_i - \alpha_i) d\theta \tag{C.33}$$

The constant $z_{i,\tau_i}$ may be determined by evaluating the RHS at $t = \tau_i$, leading to:

$$c_i'(x_{i,t}) = e^{(r+\delta)(t-\tau_i)} c_i'(x_{i,\tau_i}) + e^{rt} \int_t^{\tau_i} e^{-\delta(t-\theta)} (\omega_\theta - \mu R_i - \alpha_i) d\theta \tag{C.34}$$

## C.6 NUMERICAL VALUES USED TO PRODUCE FIG. 3.1

The simulations displayed in Fig. 3.1 were produced by using following cost function and following parameters:

$$c_i'(x_{i,t}) = C_i^m \cdot A \cdot I + C_i^m \cdot frac1 - A \frac{x_{i,t}}{X_i} \tag{C.35}$$

**Table C.1**: Parameters used to produce the figures

| | Fig. 3.1c | Fig. 3.1b | Fig. 3.1a | | Fig. 3.1c | Fig. 3.1b | Fig. 3.1a |
|---|---|---|---|---|---|---|---|
| $\delta$ | .0333 | .0333 | .0333 | $\alpha_z$ | 0 | 0 | 0 |
| $\bar{M}$ | 42 | 38 | 40 | $\alpha_h$ | .055 | .055 | .055 |
| D | 1940 | 1940 | 1940 | $\alpha_\ell$ | .1 | .06 | .06 |
| r | .05 | .05 | .05 | $C_z^m$ | 75000 | 75000 | 80000 |
| $R_z$ | 0 | 0 | 0 | $C_h^m$ | 18000 | 18000 | 18000 |
| $R_h$ | .00063 | .00063 | .00063 | $C_\ell^m$ | 35000 | 12000 | 12000 |
| $R_\ell$ | .0004 | .0004 | .0003 | $X_z$ | .00003 | .0005 | .001 |
| $H_z$ | 7500 | 7500 | 7500 | $X_h$ | .005 | .005 | .005 |
| $H_h$ | 7500 | 7500 | 7500 | $X_\ell$ | .0001 | .001 | .01 |
| $H_\ell$ | 7500 | 7500 | 7500 | A | .9 | .9 | .9 |
| | | | | 1 | 12 | 12 | 2 |

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# TABLE DES MATIÈRES DÉTAILLÉE

*Quelle place pour les aides aux technologies de réduction d'émissions en présence d'un prix du carbone ?*
*Le cas du secteur électrique,*
*When should green technology support policies supplement the carbon price?*
*The case of the electricity sector,*